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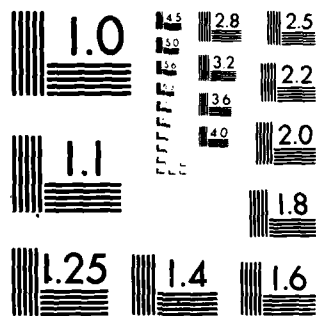DATE
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DEFENSE COMMUNICATIONS AGENCY

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COMPARISON OF PREDICTED VLF/LF SIGNAL LEVELS WITH PROPAGATION DATA

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This document is the first of a series of DCA reports issued by the Office of MEECN System Engineering and directed at definitive prediction of the time availability of LF and VLF radio systems included in the MEECN system. The sutdies described in this report are part of a continuing program to define the geophysical parameters critical to VLF and LF system performance. The program, designated the Tri-Service Propagation Program, was organized by the MEECN System Engineer to improve the accuracy and reliability of VLF/LF link integrity analysis.

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960-TP-74-5   21 January 1974

TITLE: Comparison of Predicted VLF/LF Signal Levels with
              Propagation Data

ABSTRACT: During the past 10 to 15 years, there have been several
theoretical models and associated computer programs which were
developed to compute field strength levels of VLF/LF radio waves.

          A major input to the VLF/LF propagation prediction
programs is the ionospheric model. Although numerous efforts have
been made toward defining a universal ionosphere, the lack of mea-
sured data and the variance in the results have, to date, precluded
any widespread agreement between predicted propagation ranges.

          This report correlates electron density profiles with
measured data for various geographic locations. In addition, it con-
cludes that in most cases where both VLF and LF data exist simul-
taneously over the same propagation path, the identical electron
density profile was found to approximate the measured signal level.

          A table of recommended profiles for various geographic
locations is provided as reference in making future predictions. This
data represents the most accurate profiles to date, and will be period-
ically updated to reflect the measurements being recorded under the
DCA tri-Service program.

FOR THE DIRECTOR:

OFFICIAL:

R. S. GARDINER
Captain, USN
Chief, Office of MEECN
System Engineering

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FOREWORD

This document is the first of a series of DCA reports issued by the
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tion of the time availability of LF and VLF radio systems included in
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link integrity analysis.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

I.   INTRODUCTION

[handwritten annotations: (VERY LOW frequency) (LOW frequency)]

The propagation of VLF and LF radio signals is an important factor when evaluating the performance of strategic communications. The accuracy of the prediction models is sensitive to the ionosphere profiles used in the analytic process. There are limited amounts of measured data, particularly at LF frequencies from which to derive these profiles. This technical report compares some measured data collected in the tri-Service program with predicted performance ranges to illustrate the current prediction capability and the need for improvement.

II.   THE PROPAGATION MODEL

There are three propagation theories used in the VLF/LF frequency range: (a) mode theory; (b) hop theory; and (c) zonal harmonics. The terminology relates to a physical interpretation of individual terms in the various forms of solutions to propagation equations. The propagation models, in effect, solve each of the equations described in the theory with some variation in precision and degree of detail. The mode theory model is generally referred to as WAVEGUIDE. Although there are three basic varieties of "hop" models, they are generally referred to as WAVEHOP. The zonal harmonic model is similar to WAVEHOP, however, this approach is more difficult to implement than the others and therefore is seldom used. The propagation model used in this effort is the WAVEGUIDE program developed by NELC because it most accurately describes the real world situation. It calculates the full wave solution to the propagation equations for a wave guide whose upper boundary has arbitrary electron and ion density distributions. It employs an adjustable collision frequency profile.

III.   IONOSPHERIC PARAMETERS

The ionospheric parameters needed as inputs to the WAVEGUIDE program are the electron density profile and the effective electron-neutral particle collision frequency profile.

The electron density profile parameters utilized for the computations in this report are exponential and are given in Table ES-1. The h' defines the effective height and β defines the gradient of the profile.

Table ES-1. Electron Density Profiles

DAYTIME PROPAGATION		NIGHTTIME PROPAGATION	
Exponential Form:		**Exponential Form:**	
β, km^{-1}	h', km	β, km^{-1}	h', km
0.25	74	0.5	85.5
0.30	72	0.5	87
0.30	70	0.5	90
0.50	70		
Other:		**Other:**	
WEPH IV		WEPH IV	

IV. METHODS OF EXPERIMENTAL DATA ACQUISITION

Propagation data has been collected from approximately 20 VLF/LF transmitters in the northern hemisphere through recordings aboard inflight aircraft. Supplemental data has also been made available from other sources such as that collected by the British.

V. PROPAGATION IN THE PACIFIC

Aircraft and fixed site recordings indicate that good agreement can be obtain ed by selecting a β = 0.5 km^{-1} and h' = 85.5 km for night time propagation. Daytime propagation seems most accurately described by β = 0.5 and h' = 70 km in the summer and β = 0.3 km^{-1} and h' = 72 km in the winter.

The night to night signal variability was noted to be significantly greater than day to day variability, however some of this variation may have been due to a geomagnetic storm reported to have been underway during the recording periods.

VI. PROPAGATION ACROSS THE CONTINENTAL UNITED STATES

The propagation parameters most accurately depicting conditions across CONUS are an electron density profile of β = 0.3 km^{-1} and h' = 72 km for all seasons.

VII. HIGH LATITUDE PROPAGATION

The present limited amount of data for this period leads to somewhat inconclusive results. Profiles of β = 0.3 km^{-1} and h' = 70 km and β = 0.25 km^{-1} and h' = 74 km both describe the measured data reasonably well.

VIII. PROPAGATION OVER THE GREENLAND ICE CAP

In general, experimental measurements substantiate the use of the WKB model computations using a profile of β = 0.3 km^{-1} and h' = 72 km.

IX. CONCLUSIONS

It has been determined that the following profiles tend to describe the limited available propagation data most accurately.

Table ES-2.   Recommended Profiles to Use in
WAVEGUIDE or WAVEHOP
Propagation Programs

	DAYTIME		NIGHTTIME	
	Summer	Winter	Summer	Winter
High Latitude	β=0.3, h'=72	β=0.3, h'=72	β = 0.5, h'=87	
Low Latitude	β=0.5, h'=70	β=0.3, h'=72		

There is limited knowledge available concerning the variation with season and latitude of the profiles necessary for accurate propagation prediction. The tri-Service propagation program is designed to fill this gap in knowledge necessary to make reliable VLF/LF communication system performance predictions.

1.0   INTRODUCTION

Radio signals in the very low frequency (VLF) and the lower low frequency (LF) bands suffer relatively small attenuation in propagating long distances over the earth, and they penetrate further into sea water than do waves of higher frequencies. These signals are not greatly affected by most natural-occurring ionospheric disturbances, apart from polar cap events, and VLF/LF radio communications can usually be maintained under conditions (including nuclear conditions) that make communication very difficult at higher frequencies.

Because of this, VLF and low-LF systems are prime components in the Minimum Essential Emergency Communications Network (MEECN). The Navy is highly dependent upon the VLF radio-frequency band for broadcast communications to the fleet, while the Air Force has specific interests in propagation on frequencies at the lower end of the LF range. Reliable and accurate VLF/LF propagation predictions are therefore of strategic importance to the Department of Defense, and the systems involved are part of MEECN.

Considerable theoretical work to develop a mathematical model which will accurately predict signal levels for VLF/LF frequencies has been conducted since the early 1960s. References 1, 2 and 3 (Appendix B) describe the basic theory of radio wave propagation at these long wavelengths. Detailed computational models (computer programs) based on the multimode theory, which is characteristic of propagation at these frequencies, have also been developed in recent years. These models have been found to account for the signal variability as a function of propagation distance that occurs in nature.

Computed results are, however, very sensitive to the choice of model parameters used as inputs to the calculations. In particular, the ionospheric electron density, ion density and collision frequency profiles along with proper values of the earth's magnetic field parameters, ground conductivity and dielectric constant are important quantities which are required to depict adequately the real propagational environment if reliable predictions of signals levels are to be made. In order to identify uniquely the ionospheric profiles, signal level data must be available from measurements made at many distances along a given propagation path for transmission on at least one frequency. This type of data is usually obtained by recording the transmitted fields

1

aboard an inflight aircraft. Alternately, data may be recorded at a fixed receiver site which gives the signal levels for several frequencies transmitted simultaneously over a single propagation path.

An extensive search of the literature has shown that only a small quantity of existing published data satisfies the above requirements. These measurements are mostly of VLF and are for propagation at mid latitudes. The data however, also includes signal levels recorded for propagation into the high latitudes and across the Greenland ice cap for some lower LF as well as VLF transmissions. Attempts to determine the profiles which describe some of these data will be shown to be generally successful.

This report presents a summary of the comparisons obtained between predictions made using the NELC* multimode propagation model and available experimental data that were recorded over various propagation paths. Although a comprehensive study to find the 'best-fit' profiles to the propagation data is not undertaken at this time, several simple ionospheric profiles used in the calculations describe the observed fields well enough to be used for preliminary estimates of median signal strengths available to MEECN system receivers.

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*Naval Electronics Laboratory Center, San Diego, California

2.0 THE PROPAGATION MODEL

The propagation model and computer program used to calculate signal levels is one that has been developed at NELC. This model, referred to as NELC WAVEGUIDE, obtains the full-wave solution for a waveguide whose upper boundary has arbitrary electron and ion density distributions with height and an adjustable collision frequency profile, and whose lower boundary is a smooth homogenous earth which is characterized by an adjustable surface conductivity. The model also allows for earth curvature, ionospheric inhomogeneity and anisotropy (resulting from the earth's magnetic field).

The basic propagation theory of the NELC model is described in reference 4 (Appendix B). The electromagnetic waves are considered to propagate between the earth and the ionosphere as normal modes, analogous to microwave propagation in a lossy wave-guide. The modal equation for propagation within the earth's ionos-phere waveguide is solved for as many modes as required. The eigen values so obtained are then used in a modal summation to compute the total field at some distant point from the transmitter. In many instances, the earth-ionosphere waveguide can be considered to have constant propagation properties along the transmission path. The mode sum calculations made for these cases are referred to as horizontally homogenous. In instances for which the earth-ionosphere waveguide cannot be considered as horizontally homogenous but instead varies slowly along the propagation path, a WKB* form of the mode sum is used (reference 5). This procedure was utilized in reference 6 to pre-dict VLF signals as measured aboard an inflight aircraft.

For those cases where the changes in the propagation environment are too abrupt to be adequately simulated by the WKB procedure, mode-conversion techniques must be applied. This type of computation is required for propagation through sunrise or sunset transition periods and in instances where the ground parameters change very rapidly along the propagation path. References 12 and 13 describe the NELC mode-conversion computer program and some results obtained when this model is applied to experimental data.

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*WKB - Mathematical method for approximating the fields of a VLF/ LF radio signal in regions where the propagation coefficients, such as excitation, phase velocity and attenuation, are slowly varying.

The NELC propagation model provides for the calculation of both vertical and horizontal electromagnetic fields as excited by dipoles of arbitrary orientation and elevation. The relevant equations and characteristic results are discussed in references 7, 8 and 9, while the computer program is discussed in references 10 and 11.

3.0   IONOSPHERIC PARAMETERS

The ionospheric parameters needed as inputs to the WAVEGUIDE computer program are the electron density profile and the effective electron-neutral particle collision frequency profile. Following Wait, reference 14, these terms may be assigned exponential relationships with heights and are identified by the terms β, km^{-1} and h', km.   Other electron density profile shapes are described in the literature, such as the WEPH IV as given in reference 15.

The electron density profile parameters utilized for the computations in this report are given in Table 1-1, where the values of the electron density [N(Z)] as a function of height Z in km were calculated from the equation:

$$N(Z) = \left\{ 1.43 \cdot 10^7 \frac{el}{cm^3} \cdot \exp(-0.15h') \right\} \left\{ \exp\left[(\beta - 0.15)(Z - h') \right] \right\} \quad (1)$$

Table 1-1.   Electron Density Profiles

DAYTIME PROPAGATION		NIGHTTIME PROPAGATION	
Exponential Form:		Exponential Form:	
β, km^{-1}	h', km	β, km^{-1}	h', km
0.25	74	0.5	85.5
0.30	72	0.5	87
0.30	70	0.5	90
0.50	70		
Other:		Other:	
WEPH IV		WEPH IV	

The effective electron collision frequency profile (Wait/ NELC-ν) for both day and night is computed from $\nu(Z) = \nu_0 \exp(-\alpha Z)$ where Z is height in km, ν_0 is 1.82 X 10^{11} collisions/sec, and α is 0.15 km^{-1}.

The characteristic relationship between these profiles is illustrated in Figure 1 for daytime conditions and Figure 2 for nighttime conditions (Appendix A).

4.0 METHODS OF EXPERIMENTAL DATA ACQUISITION

Propagation data have usually been obtained at NELC by recording signals originating from the Navy's VLF vertically polarized transmitters. These transmitters are listed in Table 2-1 showing the operating frequencies used in 1972.

Table 2-1. Navy VLF Transmitting
Stations

Location	Transmitter Call	Transmitter Frequency (kHz)	Effective Radiated Power dB/1KW
Cutler, Maine	NAA	17.8	29.5
Northwest Cape, Australia	NWC	22.3	31.0
Oso, Washington	NPG/NLK	18.6	24.0
Balboa, Canal Zone	NBA	24.0	21.8
Yosami, Japan	NDT	17.4	16.0
Annapolis, Maryland	NSS	21.4	27.0
Lualualei, Hawaii	NPM	23.4	28.0

Other VLF/LF transmitters from which propagation data have been obtained are listed in Table 2-2.

Table 2-2. Other VLF/LF Transmitting
Stations

Location	Transmitter Call	Transmission Frequency (kHz)	Effective Radiated Power dB 1KW
Fort Collins, Colorado	WWVL	20	unknown
Fort Collins, Colorado	WWVB	60	13
Rugby, England	MSF	60 (1970)	unknown
Preston, England	GYN	45 (1970)	unknown
Rugby, England	GBZ	19.6 (1958)	unknown
Silver Creek, Nebraska	Air Force	34.5	19
Hawes, California	Air Force	37.2	19
Annapolis, Maryland	NSS	15.5 (1958)	unknown
Lualualei, Hawaii	NPM	24.0 (1965) 26.1 (1965) 16.6 (1955)	unknown

A further source of VLF/LF propagation data is the NELC multifrequency sounder. This system is described in detail in references 16 and 17. This sounder has been used for recording both vertical incidence and oblique incidence propagation data.

The data available at NELC for comparison between computer model computations and experimentally recorded data consists of both data recorded aboard an inflight aircraft as a function of distance from the transmitter and data recorded at fixed sites as a function of time.

5.0   PROPAGATION IN THE PACIFIC AREA

Daytime - Aircraft Data: Figures 3 and 4 show the comparison between fields computed by the NELC-WAVEGUIDE computer program and data recorded aboard an inflight aircraft. These data were recorded by the Naval Research Laboratory (NRL) and are described in references 18 and 19. Figures 3 and 4 indicate that the profile $\beta = 0.5$ km^{-1}, h' = 70 km gives signal levels in close agreement with the recorded data. Figure 5 gives a summary of other comparisons using this profile, to data recorded by NELC (reference 20) and by NRL (references 18 and 19) at various frequencies for propagation over mid-latitude sea water paths in the summer.

Nighttime - Aircraft Data: Figure 6 illustrates the simulation of nighttime propagation as obtained on several radials outward from Hawaii during winter. These data are reproduced from reference 6. The theoretical curves were all computed using the WKB form of the mode sum. The electron density profile was $\beta = 0.5$ km^{-1}, h' = 85.5 km.

Most field-intensity calculations at NELC have been based on an assumed horizontally homogenous waveguide. Similar calculations have also been made for the paths included here. In this case, the waveguide mode constants computed by using magnetic parameters associated with the midpath are used for the entire path. The results obtained for the Seattle, Ontario and Wake Island paths are very similar to those obtained by using the WKB approximation. However, a significant difference is obtained for the path to Samoa. This is related to the fact that the values of the waveguide mode constants change drastically over this propagation path due to the earth's magnetic field variation in dip angle along the path.

The NPM amplitude recorded on the flight from Seattle to Hawaii is shown in Figure 6.a. The typical nighttime modal interference pattern is evident. The agreement between the measurement and the calculation is good.

The two sets of data shown in Figure 6.b, recorded on flights from Hawaii to Samoa and Samoa to Hawaii, are very similar. The similarity illustrates the degree of reproducibility of propagation conditions on the two different nights. An unusual feature of these

data is the relative lack of higher-order modal interference out to about 2.6 Mm coupled with the rapidly varying interference pattern beyond 2.6 Mm.

The data recorded during the two flights from Hawaii to Wake and Wake to Hawaii differ significantly, as shown in Figure 6.c. The Hawaii-to-Wake data indicate higher attenuation and show the more rapid oscillatory variation with distance and/or possibly time. The data recorded on the return flight have many of the characteristics of the WKB calculations shown. A profile 2 or more km higher would provide computed results with a modal interference pattern that would fit this particular data better.

The data and calculations for the Hawaii-to-Ontario path are compared in Figure 6.d. The characteristics are relatively similar. However, again, a relative shift of the modal interference pattern, such as would be produced by an increase of the ionospheric profile height by about 1 or 2 km, is needed to obtain better agreement.

The VLF data presented here indicate some variation of propagation conditions from night to night and throughout a given night. Such nighttime variability is well known. For example, the variability of phase of 10.2 kHz, as measured by Swanson using the Omega system, is equivalent to a change of phase velocity of the dominant waveguide mode of the order of ± 2 to 3 parts in 10^4. This change can be produced by a change in h' of about ± 2 to 3 km. This height variability is within the range of the profile change needed to provide better agreement between computations and data recorded during the flights from Wake to Hawaii (Figure 6.c) and Hawaii to Ontario (Figure 6.d). The former data indicate that the ionospheric reflection height was changing throughout the flight, and the latter data indicate that the reflection height was relatively stationary.

The data recorded on the flight from Hawaii to Wake (Figure 6.c), which deviate significantly from the computations for this path and from the other data recorded on this same path, indicate that the ionospheric conditions differed significantly and possibly changed with time. A geomagnetic storm was reported to have started at 1503 UT on 2 February, which was about 40 minutes after the flight terminated, and a pre-magnetic storm disturbance of the nighttime D layer may have occurred.

9

The relatively rapid oscillatory amplitude variation with distance observed beyond 2.6 Mm on the Hawaii-to-Samoa propagation path is not understood. It may be a spatial variation or a time variation. It is interesting to note that both the geographic and the geomagnetic equators intersect this path at about 2.45 Mm.

It appears that an exponential electron-density profile described by $\beta = 0.5$ km^{-1}, and 84 km $<$ h' $<$ 87 km [see equation (1), page 4] is a useful representation for nighttime conditions in that it accounts for many features of the amplitude measurements represented here.

Propagation data were also being recorded using the NELC multifrequency sounder simultaneously with the NPM data shown in Figure 6. These sounder data were recorded aboard the inflight aircraft from VLF transmissions from a horizontal VLF antenna located on the large island of Hawaii. Ten VLF frequencies were transmitted and recorded. These were approximately: 9.3, 10.9, 14.0, 15.6, 17.1, 21.8, 24.9, 26.5, 28.0 and 31.2 kHz. A detailed discussion of the data acquired and the theoretical results obtained from these data are reported in reference 21. Comparisons between WAVEGUIDE predictions and some of the multifrequency sounder data are shown in Figure 7. Here it is observed that the profile $\beta = 0.5$ km^{-1}, h' = 87 km represents these actual measured fields very well.

Daytime and Nighttime Propagation Data Recorded at Fixed Sites: Propagation measurements made at fixed sites have been reported by several investigators. These measurements almost always have been for one propagation frequency over a given path for a specific time interval. This type of data has not proven useful as far as determining any uniqueness in the form of the electron density profile of the ionospher through which the radio waves must pass. Estimates, however, of the time and seasonal variability and diurnal changes for a given frequency of propagation over the given path may be obtained. Utilization of this type of data is discussed in reference 22.

Data recorded using the NELC multifrequency sounder give signal levels at many frequencies simultaneously. With this type of data acquisition, much more data is available at the termination of the single propagation path. Using these additional data values, a more unique form of the electron density of the ionosphere may be obtained. See reference 23.

The sounder has usually been operated over the path from Hawaii to Southern California. The sites chosen to record the propagated data have been on the great circle path from the transmitter located on the large island of Hawaii to Vandenburg AFB, California (3281 km) and Johnson Valley, California (4166 km).

Comparisons of NELC WAVEGUIDE predictions with recorded sounder data are shown in Figures 8 through 13. These data were recorded at the termination of the propagation path from the Hawaii transmitter to one or the other fixed site receivers in Southern California. The frequencies transmitted consisted of 10 frequencies at VLF during four 30-hour tests between 24 September and 4 October 1968, and 9 frequencies at LF for one 30-hour test on 18-19 April 1968. The profiles used for the model computations were $\beta = 0.5$ km^{-1}, h' = 70 km for daytime and $\beta = 0.5$ km^{-1}, h' = 87 km for nighttime. For both profiles, the base of the ionosphere was assumed to be at 50 km. The method of computation assumed a horizontally homogenous waveguide. Examination of Figures 8 - 13 illustrates that the above profiles for daytime and for nighttime tend to simulate the measured propagation data fairly well for this west-to-east propagation path over the Pacific Ocean.

6.0 PROPAGATION ACROSS THE CONTINENTAL UNITED STATES

Daytime: Data obtained from propagation measurements carried out across the continental U.S. are presented in the following figures. For these computations the earth-ionosphere waveguide was considered as horizontally homogenous.

Aircraft measurements recorded by NELC and described in reference 24 are shown in Figure 14. It is of interest to note that while the profile β = 0.5 km^{-1}, h' = 70 km provided good fits to summer propagation data recorded over the Pacific Ocean, the profile β = 0.3km^{-1}, h' = 72 km tends to simulate the signal levels better for propagation over this continental path.

Other measurements of VLF/LF propagation data have been carried out by Morgan, reference 25. The measured values were made on radials extending outward from transmitters located at Fort Collins, Colorado. The transmitter frequencies were 20 kHz (WWVL) and 60 kHz (WWVB). These measurements were made from ground vehicles at various positions along each radial. All of the data were taken between 0800 and 1630 hours local standard time and, therefore, represent observed values of the daytime signal.

Table 6-1 lists the propagation paths and month of the year for which data were obtained.

Table 6-1. VLF/LF Daytime Propagation Measurements from WWVL (20 kHz) and WWVB (60 kHz), Fort Collins, Colorado

Radial Direction to:	Date Recorded
A. Fargo, North Dakota	September 1964
B. Nantucket, Massachusetts	September 1965
C. Cape Fear, North Carolina	October 1964
D. Palm Beach, Florida	September 1965
E. Brownsville, Texas	September 1965
F. Douglas, Arizona	September 1964
G. Los Angeles, California	September 1964
H. San Francisco, California	September 1964
I. Seattle, Washington	September 1965
J. Fargo, North Dakota	January 1966
K. Nantucket, Massachusetts	February 1966
L. Brownsville, Texas	January 1966

Figures 15, 16 and 17 illustrate the comparison between data recorded at 60 kHz on the radial to Palm Beach, Florida with field strengths computed for various ionospheric electron density profiles. Figure 15 indicates that the profile β = 0.5 km^{-1}, h' = 70 km does not describe the measured fields. The profiles β = 0.25 km^{-1}, and β = 0.3 km^{-1} give signal levels which are in much better agreement with data. Figure 16 shows that the WEPH IV ambient profile does not describe the measurements. Fields computed using this particular profile, where the effects of ions are included, yield identical results to those shown in this figure. Figure 17 illustrates the comparison between the data and the computed fields for the profiles β = 0.25 km^{-1}, h' = 74 km and β = 0.3 km^{-1}, h' = 72 km. The conclusion is that the latter profile fits the data more closely and therefore is used to compute signal levels for comparison with the 20 and 60 kHz measurements presented in Table 6-1. In each instance, the earth's magnetic field parameters are varied according to the particular propagation radial.

Figure 18 for 60 kHz and Figure 19 for 20 kHz show the comparisons between prediction and measurement. In these figures, the signal levels are given in dB above 1 μV/meter for 1 KW radiated power. It is observed from Figure 18 that the measurements are simulated very well for radials A, B, C and D. The other radials, however, do not give as favorable comparisons. The differences between theory and experiment are probably related to experimental accuracy, propagation path, ground conductivity, and ionospheric seasonal changes. The comparisons presented in Figure 19 tend to indicate the computed fields for the assumed electron density profile match the experimental data quite well for most of the radial paths.

7.0   HIGH LATITUDE PROPAGATION

Daytime - Aircraft Data: Some experimental data is also available from propagation into high geographic latitudes. An example comparison between experiment and prediction is shown in Figure 20. This daytime data was obtained by NELC and is described in reference 24. The trial profiles were β = 0.3 km^{-1}, h' = 70 km and β = 0.25 km^{-1}, h' = 74 km. Both profiles tend to describe the recorded data quite well.

Further comparisons between WAVEGUIDE predictions and experimental data is obtained from field strength measurements recorded aboard an inflight aircraft by Orsborn in 1970. This data is described in reference 26. For this data, flights were made along a path from Offutt AFB, Omaha, Nebraska to Fort Yukon, Alaska. The LF transmissions monitored were from the Silver Creek, Nebraska transmitter on 34.5 kHz. A second measurement path was from Hawes, California to Fort Yukon where the transmissions were from the 37.2 kHz transmitter at Hawes. Data were recorded over both paths for both daytime and nighttime flights. Note that the measured data are primarily of a relative nature and the field intensity measurements can only be said to be approximate. Orsborn's data is shown in Figures 21 through 27.

For these calculations the actual aircraft altitude is unknown, however, calculations were made for various receiver heights 0, 3, 6 and 9 km. In these figures, the term "z-component" refers to the vertical E field at the receiver. Examination of the figures indicates that while the profile β = 0.25 km^{-1}, h' = 74 km, gives signal levels which approximate the data shown in Figure 20 quite well; the fit to the Orsborn data is quite poor. The profile β = 0.5 km^{-1}, h' = 70 km simulates the data, as shown in Figure 22 much better. This profile gives field strength values which tend to duplicate the measured null at 0.5 Mm. It also gives good agreement to the data out to 2.5 Mm. It does not appear probable that use of the WKB procedures, where the ground conductivity would be modified near the end of the path and where the earth's magnetic field would be allowed to vary, could result in a better fit to the Silver Creek data using the β = 0.5 km^{-1}, h' = 70 km profile. Figure 23 is provided for general information.

14

<u>Nighttime - Aircraft Data</u>: Nighttime field strength measurements, as recorded by Orsborn during flights from the Silver Creek transmitter to Fort Yukon, Alaska, are shown in Figures 24 and 25. The electron density profiles utilized were $\beta = 0.5$ km^{-1}, h' = 87 km and WEPH IV, reference 15. Again, the aircraft flight altitude is unknown so that field strengths were computed for several values of the receiver height (RALT, km - - 0, 3, 6, 9 and 12) were used. Also, the vertical electric field is denoted as "z-component". Neither profile can be said to produce the better fit to the data; however, both results are encouraging.

Another series of aircraft-flight measurements made by Orsborn consisted of measuring nighttime transmissions from Silver Creek to Thule, Greenland. The data and predictions are shown in Figures 26 and 27. The experimental values represent an average of repeated measurements made along the same path. It appears that the horizontally homogenous calculations shown in Figure 26 do fit the data rather well except for the position of the null in the vicinity of 1 Mm. The WKB procedure on the other hand does not improve the prediction as shown in Figure 27 and in fact gives very different field strengths at 3.5 Mm. These results may be explained by the fact that the actual aircraft flight path may not have included the various ground conductivities that were used in the calculations. The propagation path is assumed to be along a great circle path between transmitter and receiver. In actuality, the paths of the aircrafts, aboard which the data were recorded, varied from the true great circle paths.

15

8.0   PROPAGATION OVER THE GREENLAND ICE CAP

Experimental measurements obtained during aircraft flights over the Greenland ice cap will be examined in this section. Firstly, Burgess (reference 27) has recorded data from transmissions at 45 and 60 kHz originating in England on a flight over the ice cap and terminating in Sondrestrom, Greenland. Comparisons of these data with WAVEGUIDE predictions are shown in Figures 28 through 31.

Other propagation measurements of transmissions made over the Greenland ice cap have been carried out by NELC and are discussed in reference 24. These consist of flights from Seattle over the Greenland ice cap to Norway and from London over the ice cap to Fairbanks, Alaska. Comparisons with WAVEGUIDE predictions are shown in Figures 32 and 33. In general, the WKB model computations tend to approximate the experimental data quite well. The profile $\beta = 0.3$ km^{-1}, h' = 72 km tends to fit the Burgess data best. For the NELC data, $\beta = 0.25$ km^{-1}, h' = 74 km provides the best fit to the measurement.

In an attempt to simulate the propagation transition from sea water to Greenland ice, the above NELC data at 18.6 kHz and 19.6 kHz are compared to fields computed using the NELC mode-conversion program (reference 12) in Figures 34 and 35. The figures illustrate that the mode-conversion calculation describes the detailed variations in signal level observed as the radio wave crosses onto the ice cap.

9.0 CONCLUSION

This report has illustrated the ability of the NELC WAVEGUIDE computer program to predict realistic VLF/LF signal levels. Comparisons between predicted and measured values of field strength, as presented in the figures show that the complicated interference structure characteristic of radio wave propagation at these frequencies may be simulated very closely if the propagation parameters are known with enough accuracy.

It has been determined that the following profiles tend to describe the limited amount of available propagation data to varying degrees of exactness. Table 9-1 summarizes the results.

Table 9-1. Descriptive Electron Density Profiles for
Various Geographic Locations

Propagation Path	Season	Electron Density Profile Daytime β,km^{-1},h',km	Nighttime β,km^{-1},h',km
Midlatitude (Pacific)	Summer	0.5, 70	- - -
	Fall	0.5, 70	0.5, 87
	Winter	- - - -	0.5, 87
	Spring	0.5, 70	0.5, 87
Midlatitude (Continental U.S.)	Summer	0.3, 72	- - - -
	Fall	0.3, 72	- - - -
	Winter	- - - -	- - - -
	Spring	- - - -	- - - -
High-latitude (Continental U.S. over Canada to Alaska and Greenland)	Summer	0.3, 70; 0.25,74	- - - -
	Fall	- - - -	- - - -
	Winter	0.5, 70	0.5, 87
	Spring	- - - -	- - - -
Arctic Region (Canada and Greenland ice cap)	Summer	0.3, 72	- - - -
	Fall	- - - -	- - - -
	Winter	- - - -	- - - -
	Spring	- - - -	- - - -

In most cases where both VLF and LF data existed simultaneously over the same propagation path, the identical electron density profile was found to approximate the measured signal levels.

17

It is probable that other choices of electron density profiles can be found that will fit the propagation data more closely. A profile inversion procedure as developed by Shellman (reference 28) should be applied to the measured fields in an attempt to determine such profiles. Also, more accurate information is needed on the numberical values of other propagation parameters such as ground conductivity along the flight path and the actual path followed by the inflight recording aircraft.

In the past, much of the VLF/LF propagation data reported in the literature has consisted of measurements made at a single receiver site on one propagation frequency over a given path. This type of data has not proven useful as far as determining any uniqueness in the form of the electron density profile of the ionosphere through which the radio wave must pass. Data recorded using the NELC multi-frequency sounder, on the other hand, give signal levels at many frequencies simultaneously. With this type of data acquisition, much more data are available at the termination of a single propagation path, and in the case where the receiver is placed aboard an inflight recording aircraft, multi-frequency data is obtained as a continuous function of distance. The availability of such multiple frequency data provides a facility for determining a much more unique form of the ionospheric electron density profile than has previously been possible.

The propagation theory which is implemented in existing computer programs, such as the NELC WAVEGUIDE, is probably sufficient for computing signal levels as a function of frequency and distance so that very little additional effort needs to be expended on the analytical aspect of the propagation. However, in order to make accurate predictions of VLF/LF signal levels on a global basis, the propagation environment, particularly the electron density profile of the ionosphere, must be known more precisely than it is at this time. The ionosphere itself is sufficient variable with respect to geographic longitude and latitude, as well as to diurnal and seasonal changes, that the ability to make precise predictions of propagated fields for all propagation paths and for all seasons has been quite limited. If only existing data are considered in determining ionospheric profiles, propagation predictions must be based on relatively few, isolated data sources. To produce more reliable and accurate VLF/LF propagation predictions for utilization in the development of Naval and Air Force operational systems, additional data for propagation in all geophysical environments is needed. This will require an extensive measurement program for recording propagation data over many propagation paths at many frequencies during the

18

four seasons. This program should include measurements of signal amplitude and phase as recorded vs time and/or distance on several frequencies simultaneously so as to obtain the most reliable and definitive information concerning the effective long path propagation medium. Signlas to be measured should include those radiated by airborne long-trailing wire antennas, fixed site operational VLF and LF communication and navigation systems and experimental transmitting facilities such as the NELC multifrequency sounder which permits data to be recorded on 10 to 20 frequencies simultaneously ranging from 9 to 60 kHz.

The most important propagation paths over which data should be obtained are:

- Those involving primarily sea water at nearly constant geomagnetic latitude where the propagation paths may be assumed to be horizontally homogenous, thus simplifying interpretation and analysis of the data.

- High latitude paths, i. e., those passing through polar cap region and auroral zone. Only a very limited amount of information and data is available concerning the effective ionospheric profiles that support long distance VLF/LF propagation in the higher latitudes. Paths which pass through these regions will provide an opportunity to determine the electron density profiles as produced by solar-geophysical phenomena such as PCA events, sola flares and geomagnetic storms.

- Paths which contain highly varying ground conductivities, such as propagation across Canada and over the Greenland ice cap, should also be included to examine further the utility of the prediction model in simulating these propagation conditions.

Once a sufficient amount of experimental data has been acquired, the ionospheric parameters, i.e., electron density profiles, which describe the propagation environment may be determined with sufficient accuracy to insure reliable predictions of VLF/LF signal levels. These predictions can be used, together with data on signal variability, atmospheric noise, and system parameters, to compute the time availability of MEECN VLF/LF links.

19

APPENDIX A - FIGURES 1 THRU 35

Figure 1. Daytime Electron Density Profiles and Collision Frequency Profiles

A-1
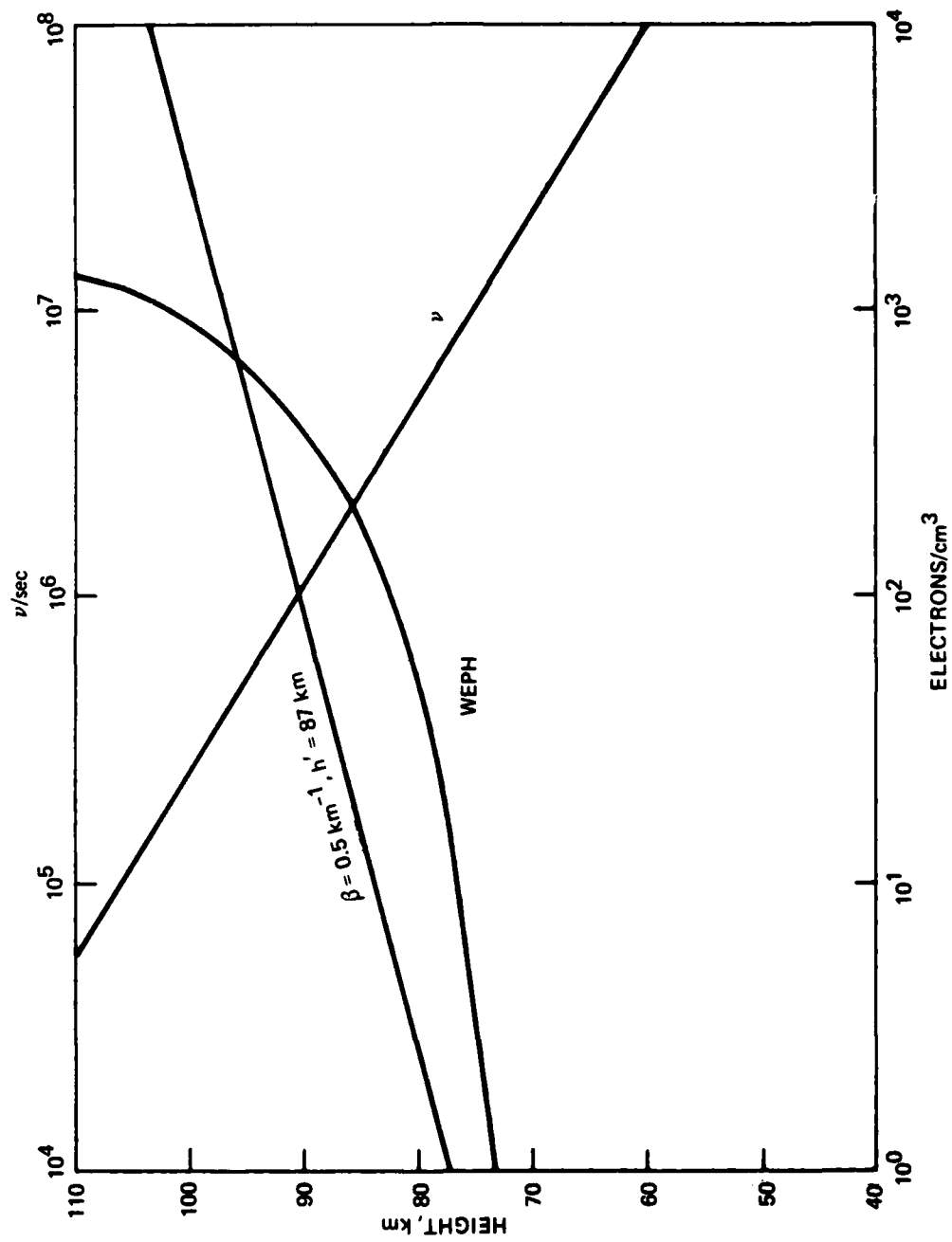
Figure 2. Nighttime Electron Density Profiles and
Collision Frequency Profile

A-2

Figure 3. Propagation over the Pacific Ocean
(daytime, summer) (24 kHz)
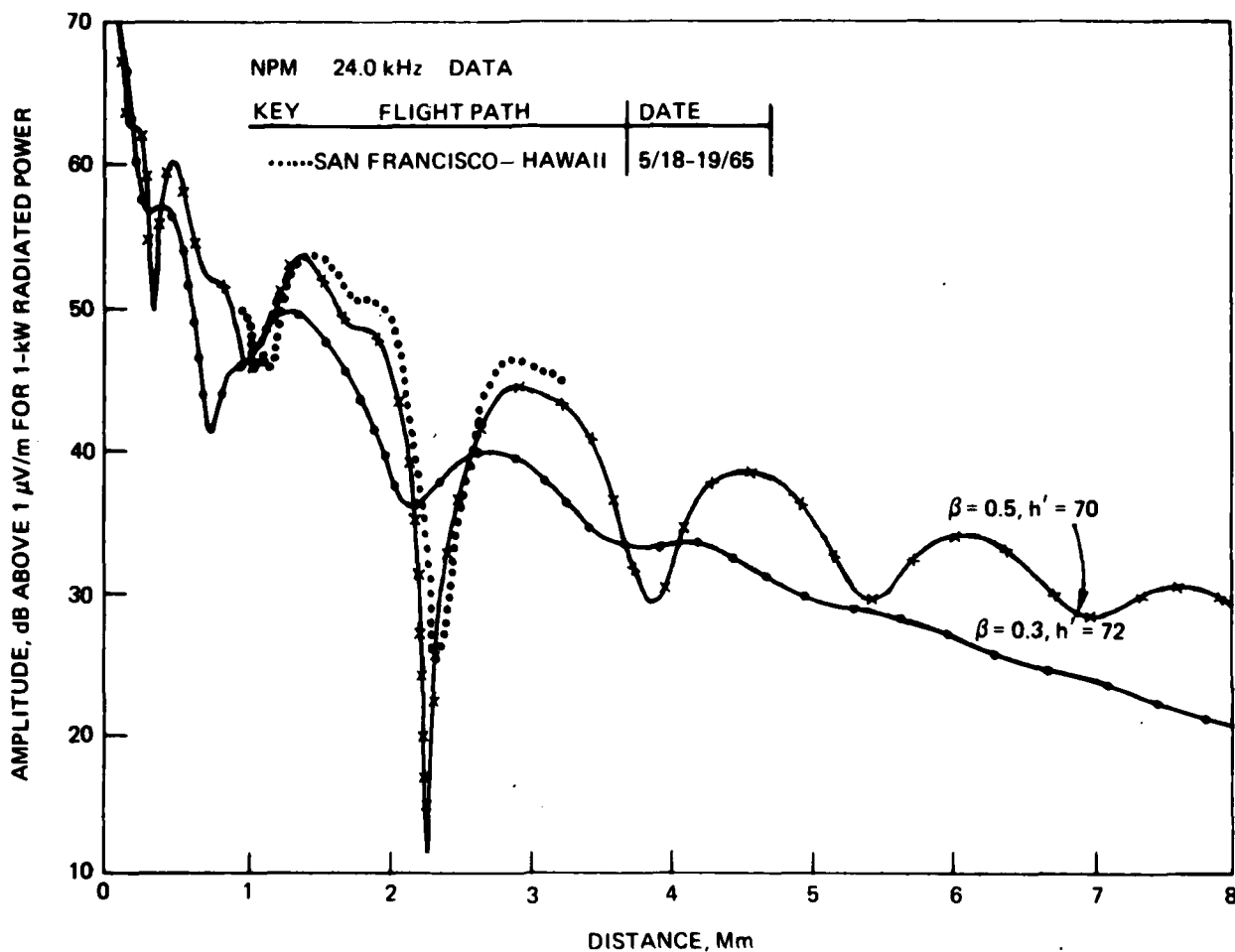
Flight Path: San Francisco to Hawaii (daytime)
Ground Conductivity: Sea water, σ = 4 mhos/meter
Transmitter: NPM, Hawaii (24.0 kHz)
Date: June 1965
Electron Density Profiles: β = 0.5 km^{-1}, h' = 70 km with the base of
the ionosphere at 50 km, and
β = 0.3 km^{-1}, h' = 72 km with the base of
ionosphere at 30 km.
Method of Computation: Horizontally homogenous waveguide

A-3

Figure 4.   Propagation over the Pacific Ocean
(daytime, summer) (26.1 kHz)
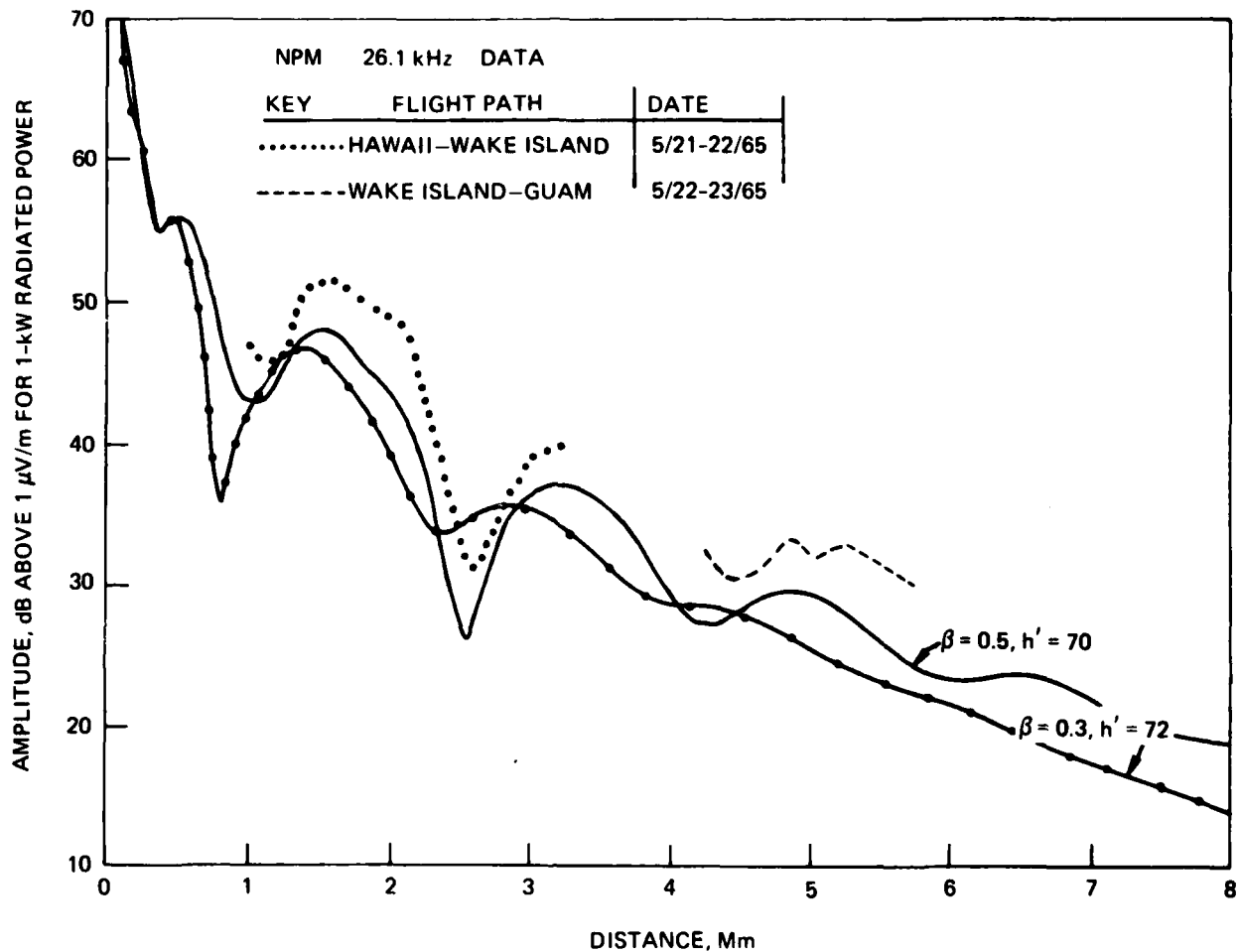
Flight Path: Hawaii to Wake Island to Guam (daytime)
Ground Conductivity: Sea water
Transmitter: NPM, Hawaii at 26.1 kHz
Date: June 1965
Electron Density Profiles: β = 0.5 km^{-1}, h' = 70 km with base of the
ionosphere at 50 km, and
β = 0.3 km^{-1}, h' = 72 km with base of the
ionosphere at 30 km.
Method of Computation: Horizontally homogenous waveguide

Figure 5. Propagation over the Pacific Ocean (daytime, summer)
(various VLF frequencies) (β=0.5 km^{-1},h'=70km)

FROM NPM, HAWAII

16.6 kHz TO WAKE AND TOKYO
(NELC 8/56, 8/56)

19.8 kHz TO WAKE AND GUAM
(NRL 5/65)

26.1 kHz TO WAKE AND GUAM
(NRL 5/65)

16.6 kHz TO SAN DIEGO
(NELC 8/56)

19.8 kHz TO SAN FRANCISCO
(NRL 5/65)

24.0 kHz TO SAN FRANCISCO
(NRL 5/65)

20 dB

DISTANCE, Mm
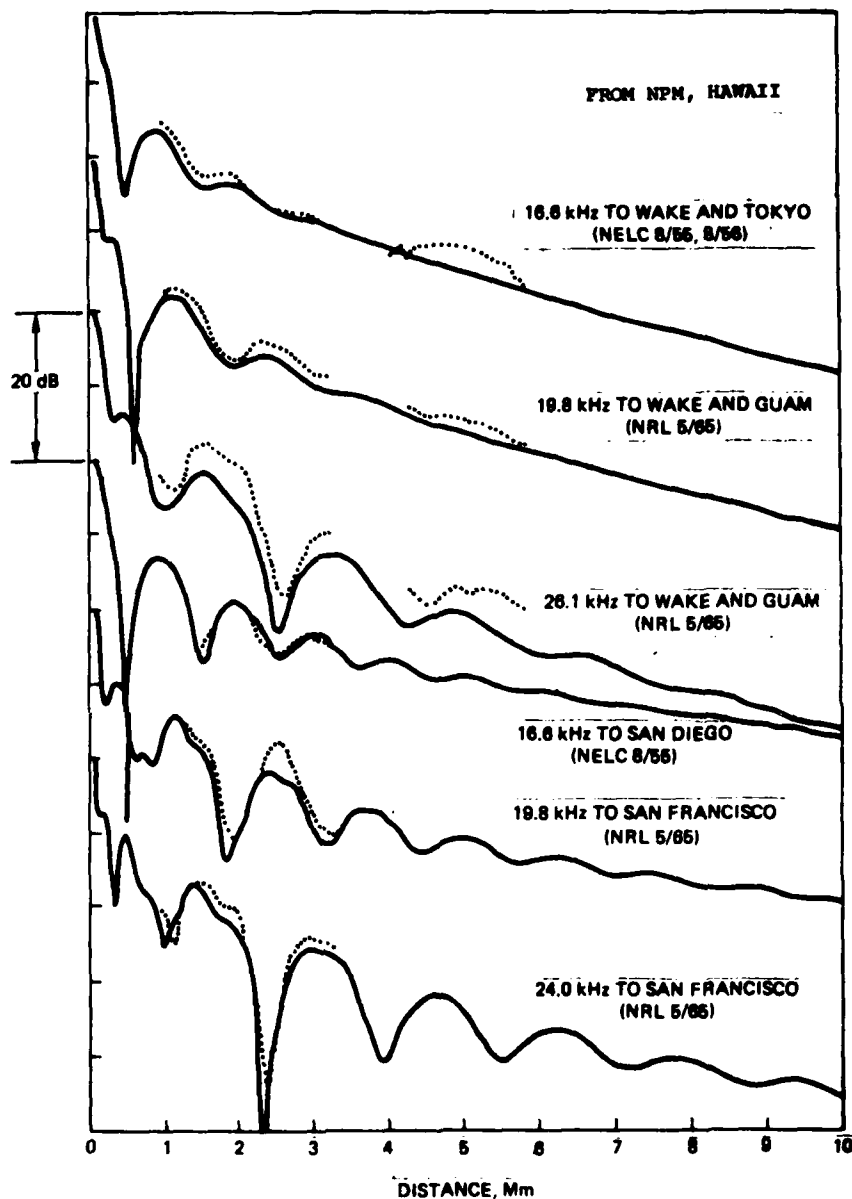
Flight Path: Various radials from Hawaii (daytime)
Ground Conductivity: Sea water
Transmitter: NPM, Hawaii
Electron Density Profile: β = 0.5 km^{-1}, h' = 70 km with base of the
ionosphere at 50 km.
Method of Computation: Horizontally homogenous waveguide

A-5
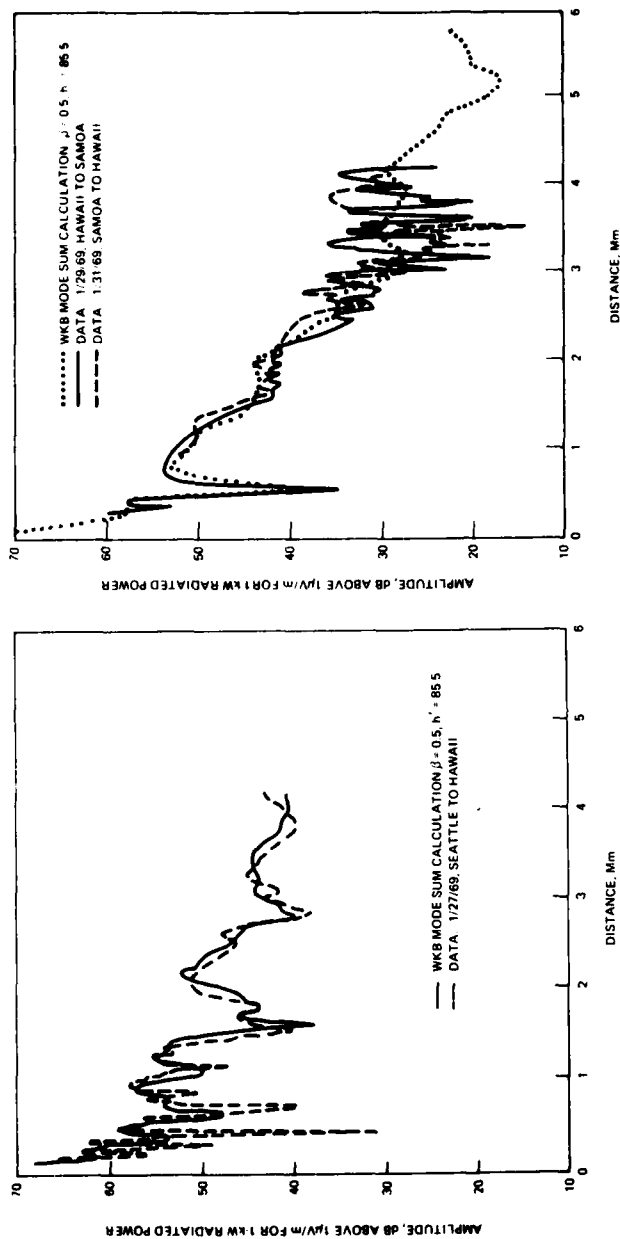
FIG. A. Comparison of measured data with **WKB** mode sum calculations for the Hawaii (NPM, 23.4 kHz)-to-Seattle propagation path.

FIG. B. Comparison of measured data with **WKB** mode sum calculations for the Hawaii (NPM, 23.4 kHz)-to-Samoa propagation path.

Flight Paths: Hawaii from Seattle, Washington; to and from Samoa; to and from Wake Island; and to Ontarion, California. (nighttime)

Ground Conductivity: Sea water

Transmitter: NPM, Hawaii (23.4 kHz)

Date: February 1969

Electron Density Profile: $\beta = 0.5 \ km^{-1}$, $h' = 85.5$ km with the base of the ionosphere at 50 km.

Method of Computation: WKB approximation.

Figure 6.   Propagation over the Pacific Ocean (Nighttime, Winter) (23.4 kHz) (reference 6)

A-6
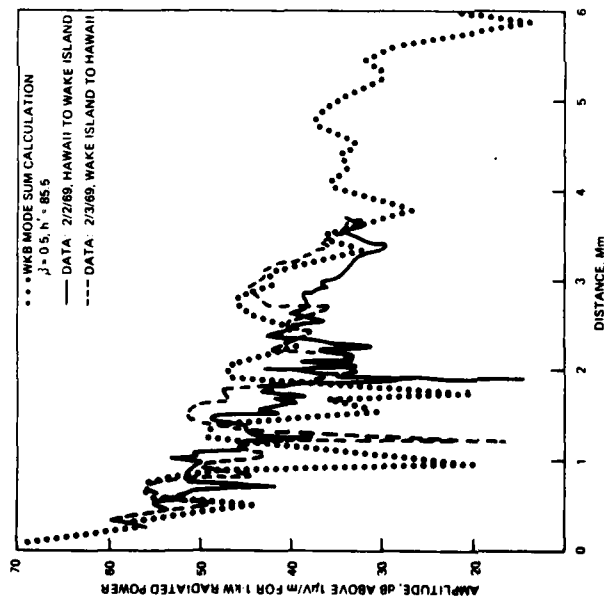
FIG. C. Comparison of measured data with WKB mode sum calculation for the Hawaii (NPM, 23.4 kHz)-to-Wake Island propagation path.
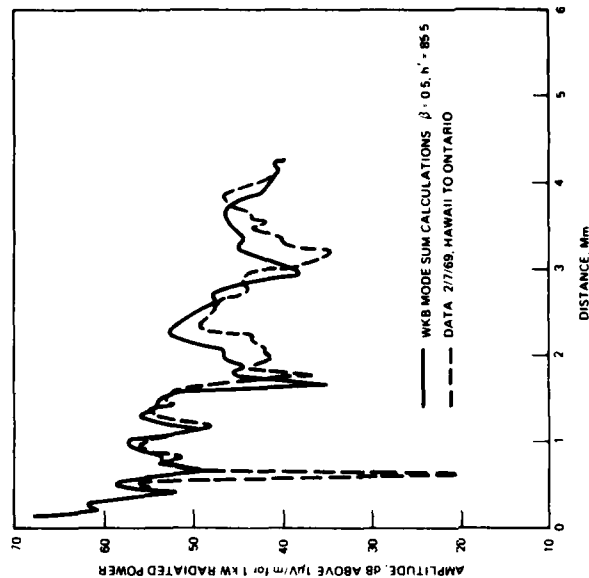
FIG. D. Comparison of measured data with WKB mode sum calculation for the Hawaii (NPM, 23.4 kHz)-to-Ontario (California) propagation path.

Flight Paths: Hawaii from Seattle, Washington; to and from Samoa; to and from Wake Island; and to Ontarion, California.

Ground Conductivity: Sea water (nighttime)

Transmitter: NPM, Hawaii (23.4 kHz)

Date: February 1969

Electron Density Profile: $\beta = 0.5 \text{ km}^{-1}$, $h' = 85.5$ km with the base of the ionosphere at 50 km.

Method of Computation: WKB approximation.

Figure 6 (CONTINUED)

Figure 7. Multifrequency Sounder Data over the Pacific-Hawaii to Ontario-California (Nighttime, Winter)
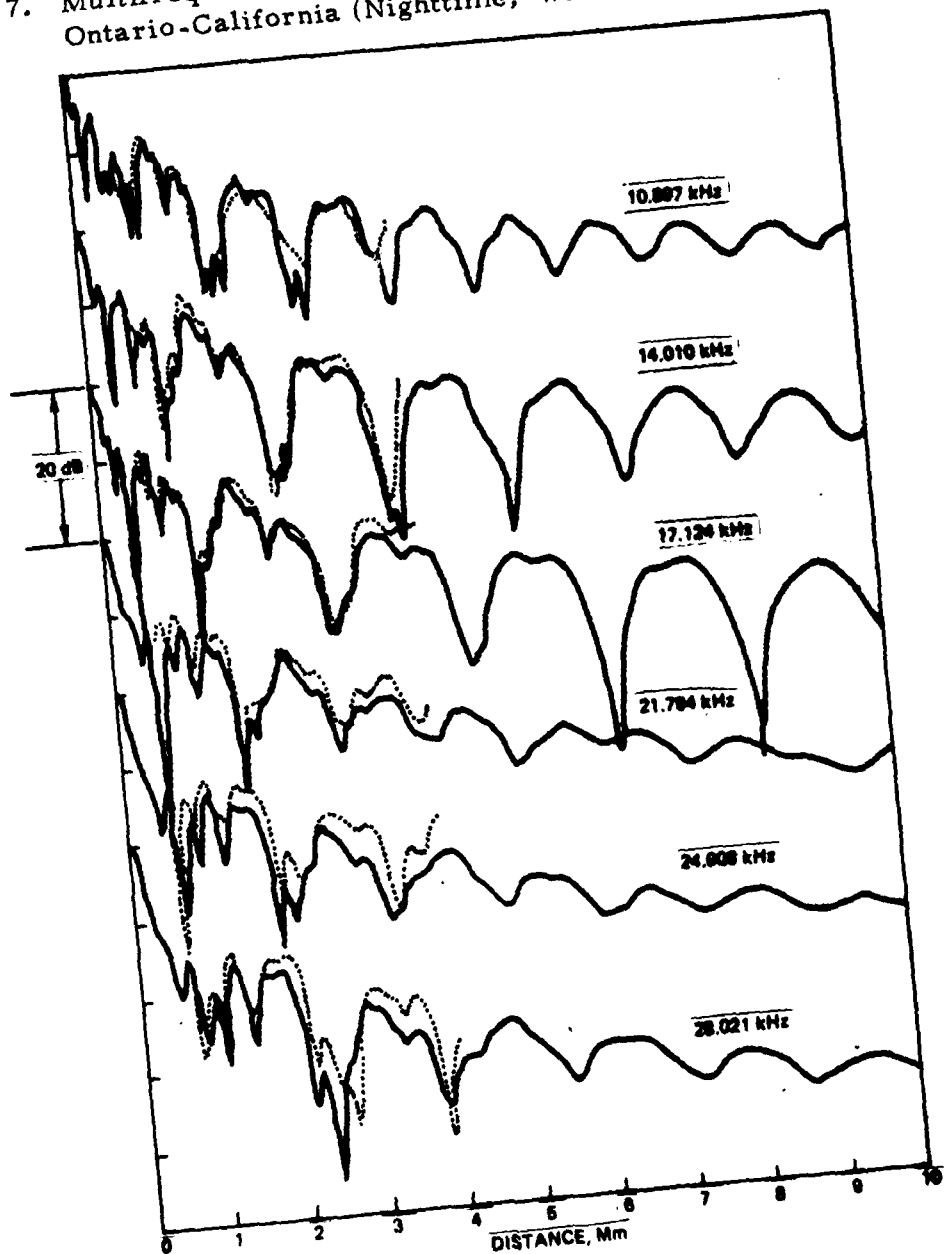
Flight Path: Hawaii to Ontario, California (nighttime)
Ground Conductivity: Sea water
Transmitter: NELC multi-frequency sounder, Hawaii
Date: February, 1969
Electron Density Profile: $\beta = 0.5 \text{ km}^{-1}$, $h' = 87$ km with the base the ionosphere at 50 km.

Method of Computation: Horizontal homogenous waveguide

A-8

Figure 8. Propagation over the Pacific Ocean to Fixed Receiver Site (Daytime, Fall) (VLF)
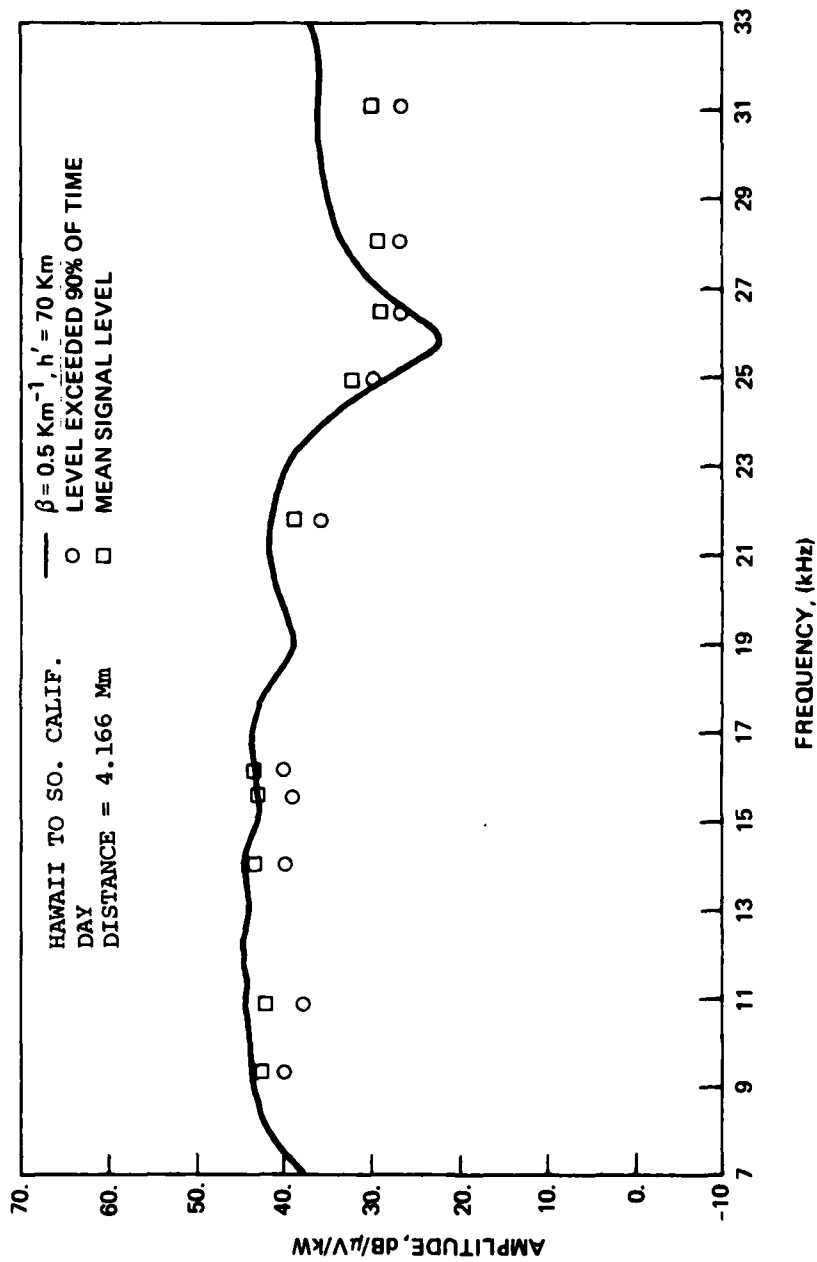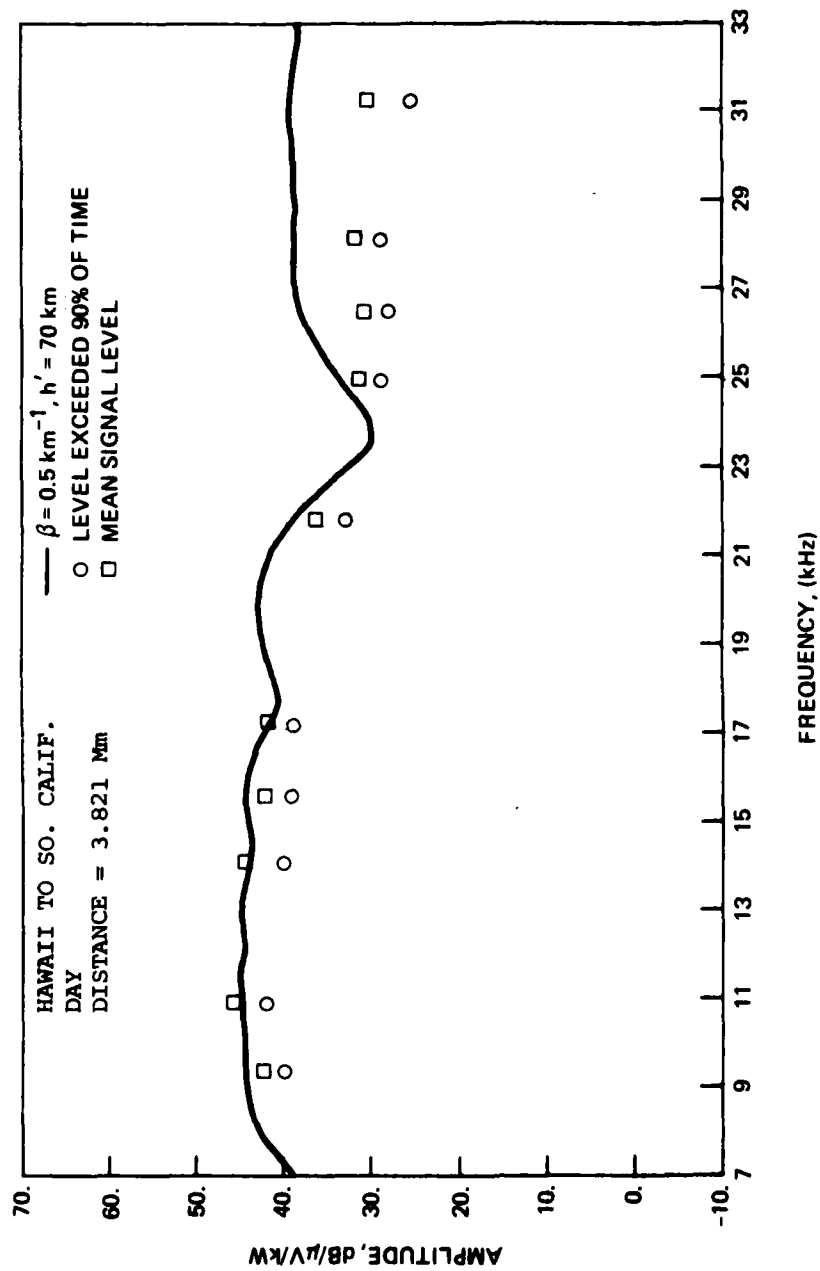
Propagation Path: Hawaii to Southern California, (4166 km)
Ground Conductivity: Sea water
Transmitter: NELC multi-frequency sounder, VLF
Date: 6-7 March 1967

A-9

Figure 9. Propagation Over the Pacific Ocean to Fixed Receiver Site.

Figure 10. Propagation Over the Pacific Ocean to Fixed Receiver Site

A-11

HAWAII TO SO. CALIF.
NIGHT
DISTANCE = 4.166 Mm

——— $\beta = 0.5$ km^{-1}, $h' = 87$ km
○ LEVEL EXCEEDED 90% OF TIME
□ MEAN SIGNAL LEVEL

FREQUENCY, kHz

AMPLITUDE, dB/µV/kW
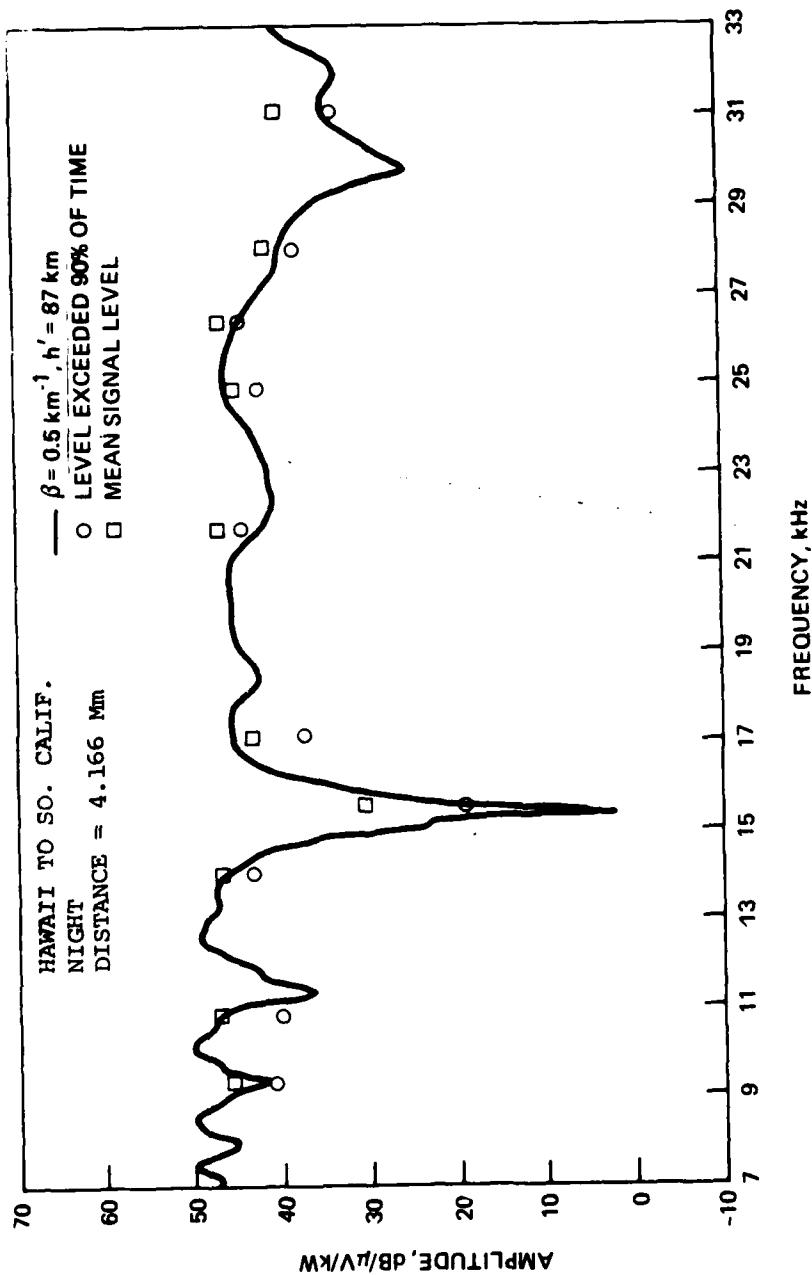
Propagation Path: Hawaii to Southern California (4166 km)
(nighttime)

Transmitter: Multifrequency Sounder, VLF
Date: September-October 1968

Figure 11. Propagation Over the Pacific Ocean
to Fixed Receiver Site

A-12

Figure 12. Propagation over the Pacific
Ocean to Fixed Receiver Site
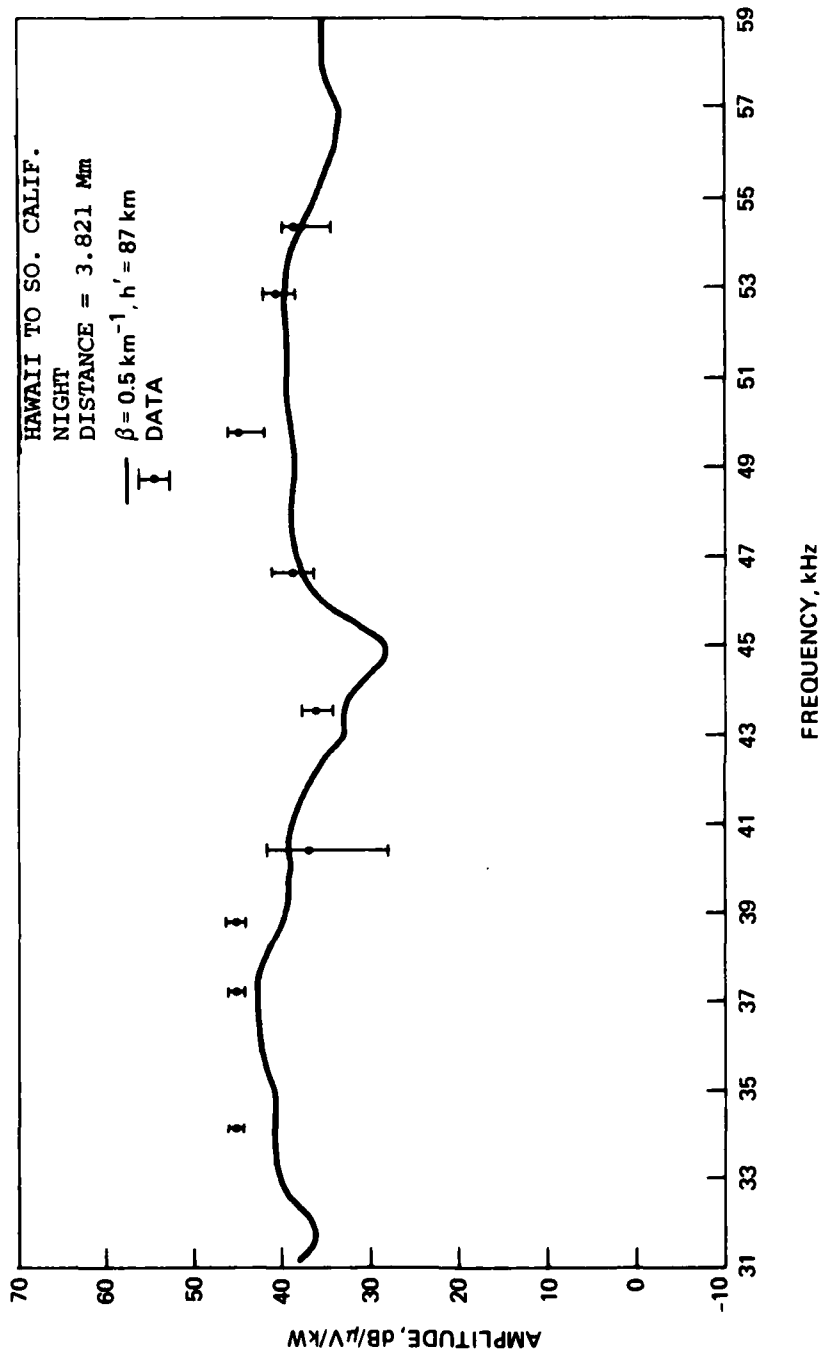
Propagation Path: Hawaii to Southern California (3821 km), (nighttime)
Transmitter: Multi-frequency sounder, VLF
Date: September - October 1968

A-13

Figure 13. Propagation over the Pacific
Ocean to Fixed Receiver Site

Propagation Path: Hawaii to Southern California (3821 km), (nighttime)
Transmitter: Multi-frequency sounder, LF
Date: 18-19 April 1968

A-14

Figure 14. Propagation Across the Continental
United States
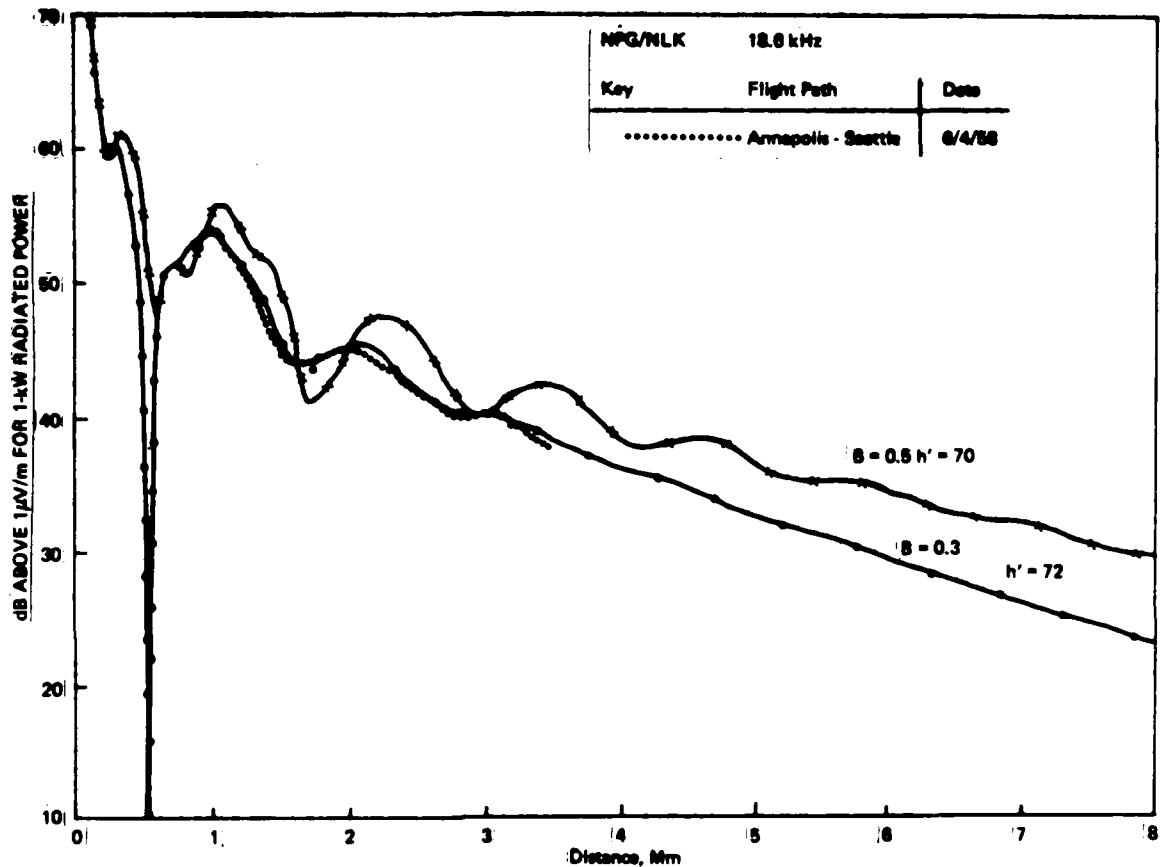
Flight Path: Annapolis, Maryland to Seattle, Washington, (daytime)
Ground Conductivity: Land σ = 0.01 mhos/meter
Transmitter: NPG/NLK, Seattle at 18.6 kHz
Date: June 1958
Electron Density Profiles: β = 0.5 km^{-1}, h' = 70 km with the base of
the ionosphere at 50 km, and
β = 0.3 km^{-1}, h' = 72 km with the base of
the ionosphere at 30 km.
Method of Computation: Horizontally homogenous waveguide

A-15

Figure 15. Propagation Across the Continental
            United States
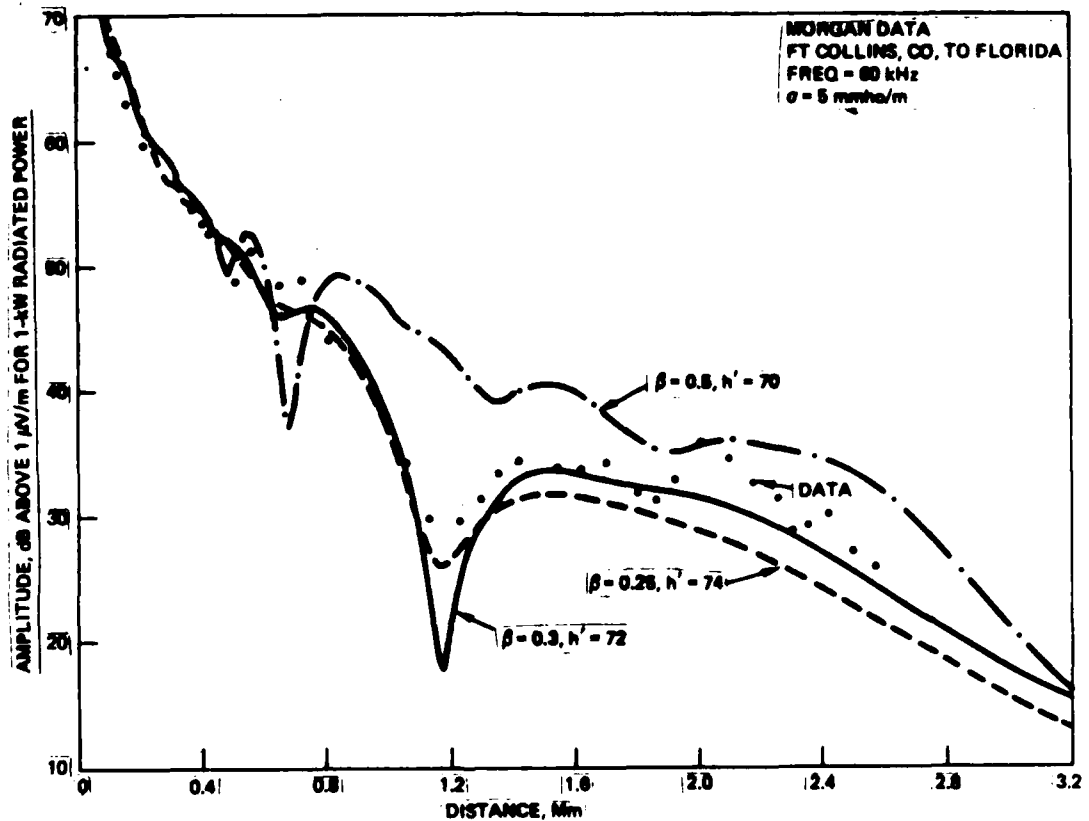
Propagation Path: Fort Collins, Colorado to Palm Beach, Florida
Ground Conductivity: Land, σ = 0.005 mhos/meter
Transmitter: WWVB, Colorado at 60 kHz
Date: September 1965
Electron Density Profiles: β = 0.5 km^{-1}, h' = 70 km with the base of
                            the ionosphere at 50 km, and
                            β = 0.3 km^{-1}, h' = 74 km with the base of
                            the ionosphere at 20 km.
Method of Computation: Horizontally homogenous waveguide

A-16
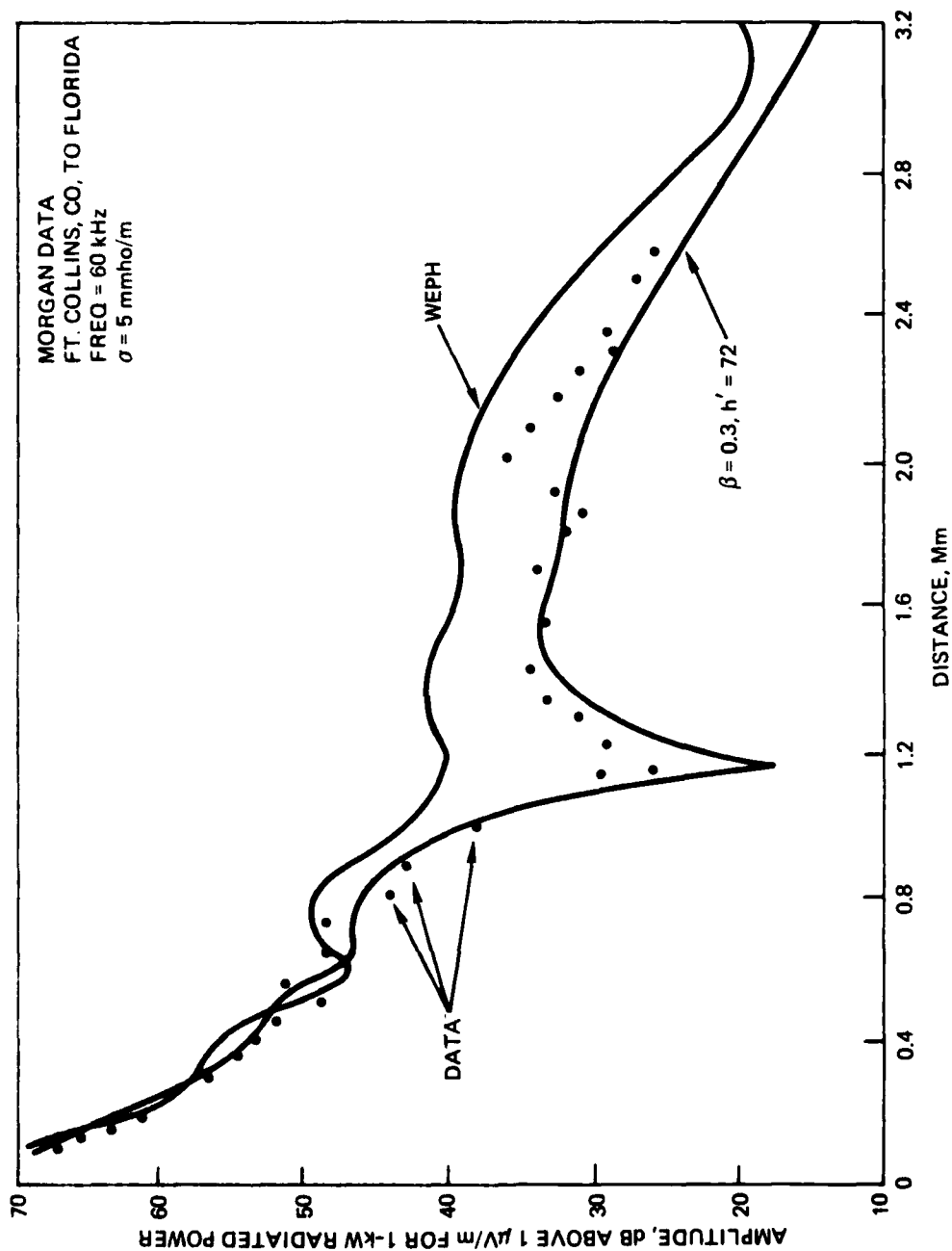
Parameters are the same as those of figure 15 except that the electron density profiles considered are the β = 0.3 km^{-1}, h' = 72 km and the WEPH IV daytime profile taken from reference 15.

Figure 16. Propagation Across the Continental United States

Figure 17.   Propagation Across the Continental
United States
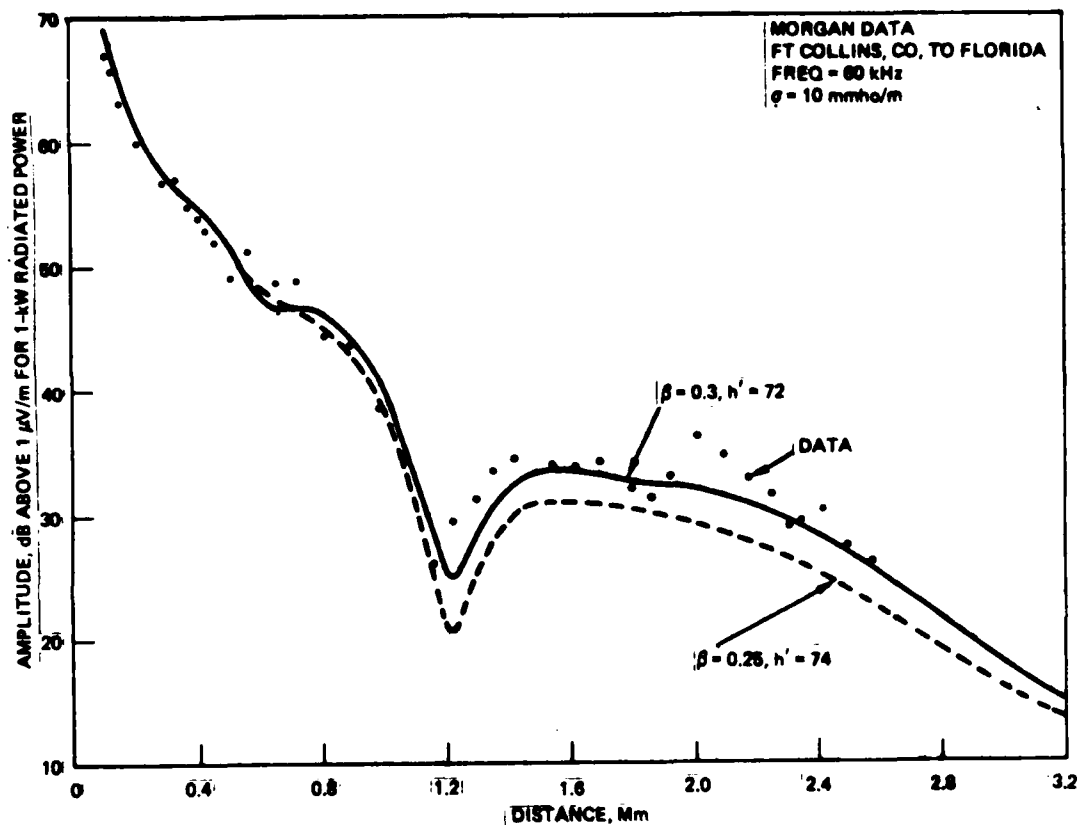
Again the parameters are the same as those of figure 15 except that
a more ideal value of the earth's conductivity is used for this path
($\sigma_{-1} = 0.01$ mhos/meter). The electron density profiles are $\beta = 0.3$
km^{-1}, h' = 72 km with the base of the ionosphere taken as 30 km and
$\beta = 0.25$ km^{-1}, h' = 74 km with the base of the ionosphere taken as
20 km.

A-18

Figure 18. Propagation Across the Continental United States

FREQ = 60 kHz
DATA = O
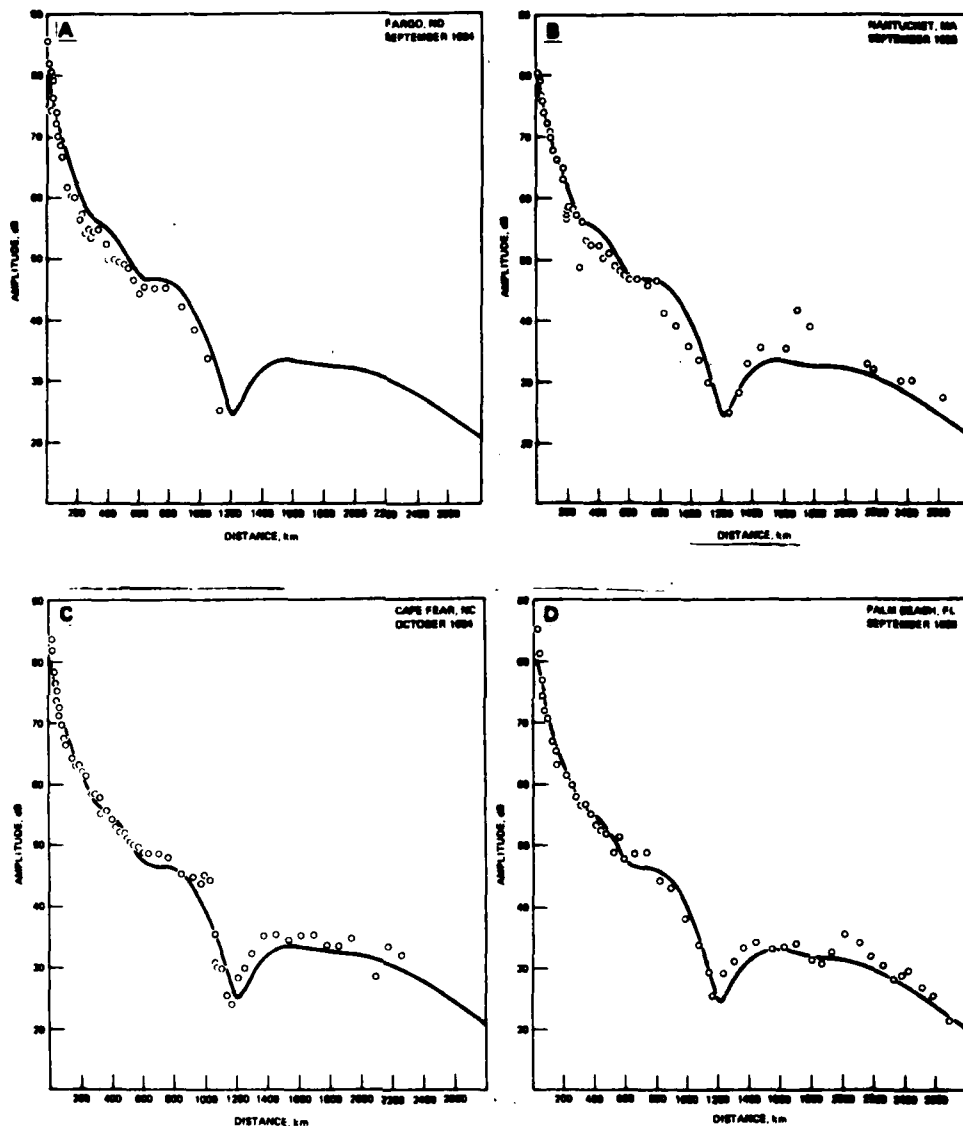
Propagation Path: Nine radials outward from Fort Collins, Colorado
                         (daytime)
Ground Conductivity: Land' σ = 0.01 mhos/meter
Transmitter: WWVB, Fort Collins, Colorado at 60 kHz
Date: September 1964, 1965; October 1964; January 1966; February 1966.
Electron Density Profile: β = 0.3 km^{-1}, h' = 72 km with the base of
                                    the ionosphere at 30 km.
Method of Computation: Horizontally homogenous waveguide

A-19
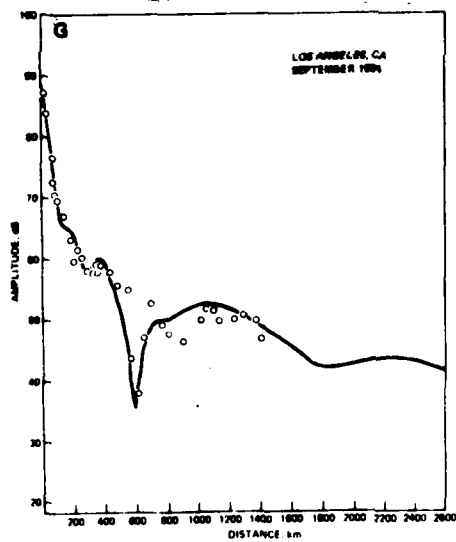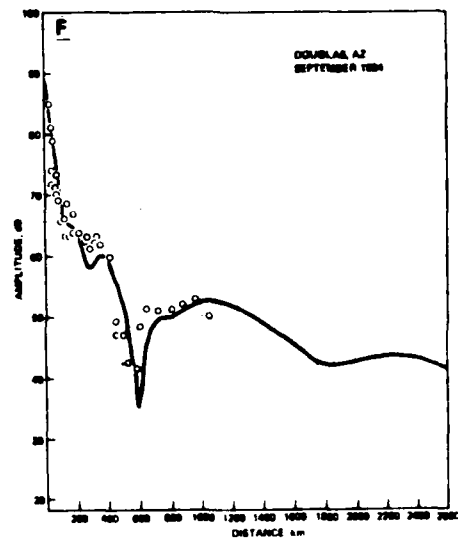
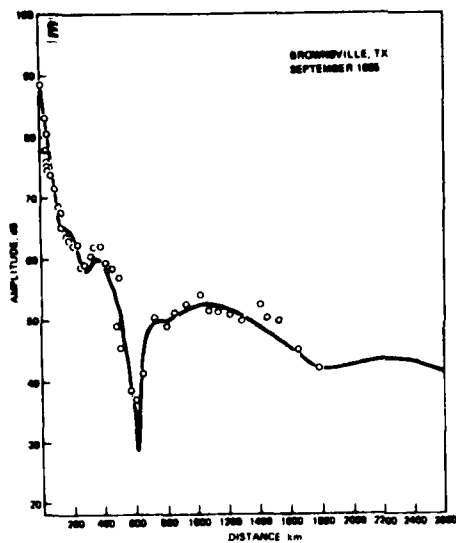Figure 18. (CONTINUED) (Fall) (60 kHz)

FREQ = 60 kHz
DATA = O
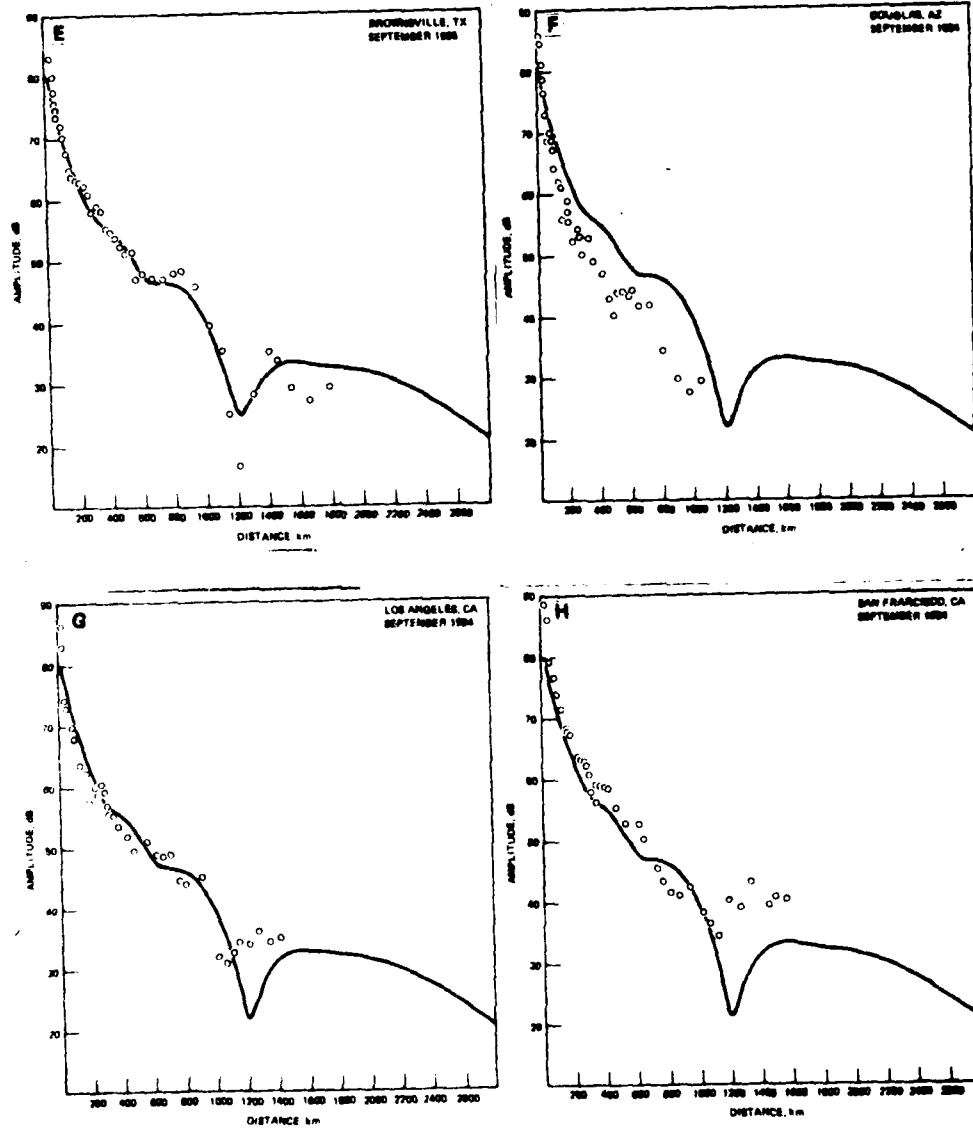
Figure 18. (CONTINUED) (Fall, Winter) (60 kHz)

A-21
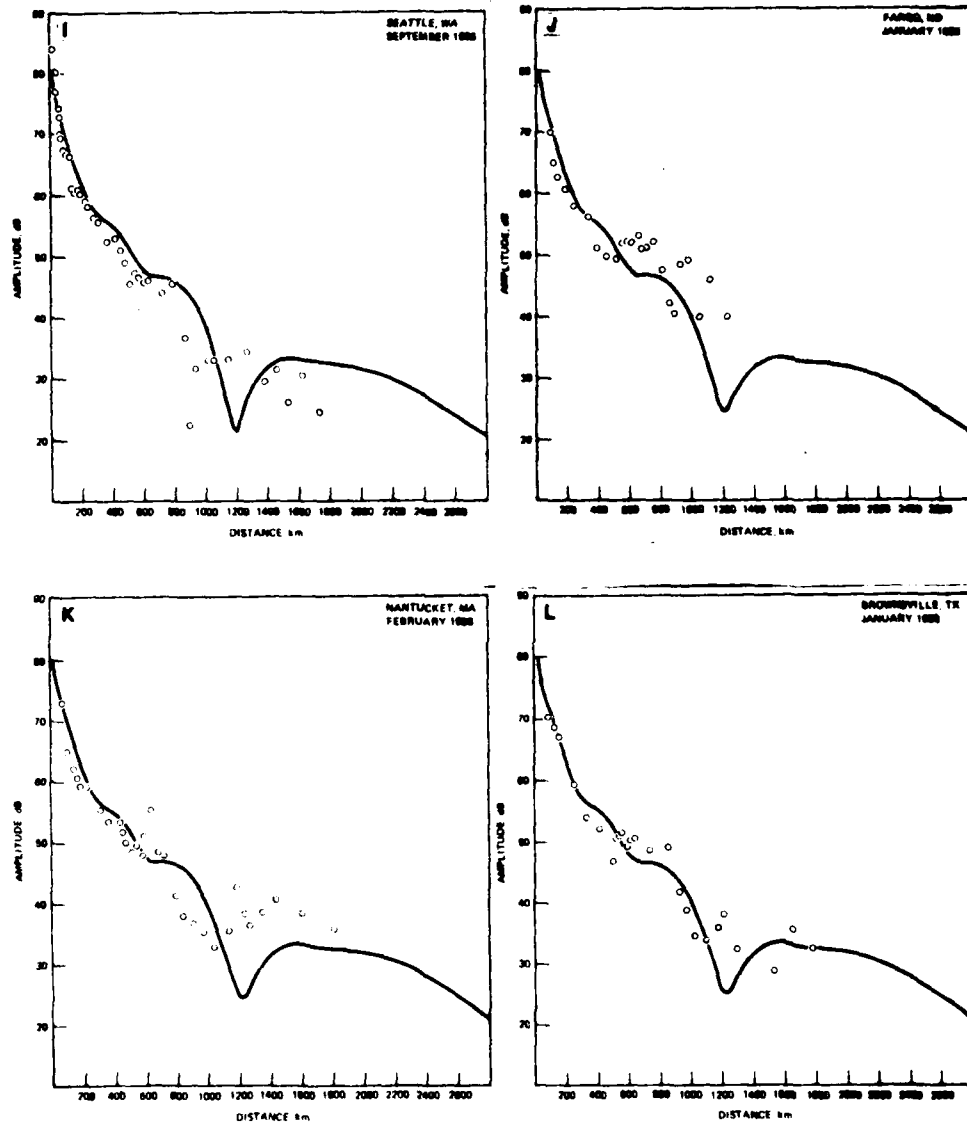
Figure 19.   Propagation Across the Continental United States

FREQ = 20 kHz
DATA · O
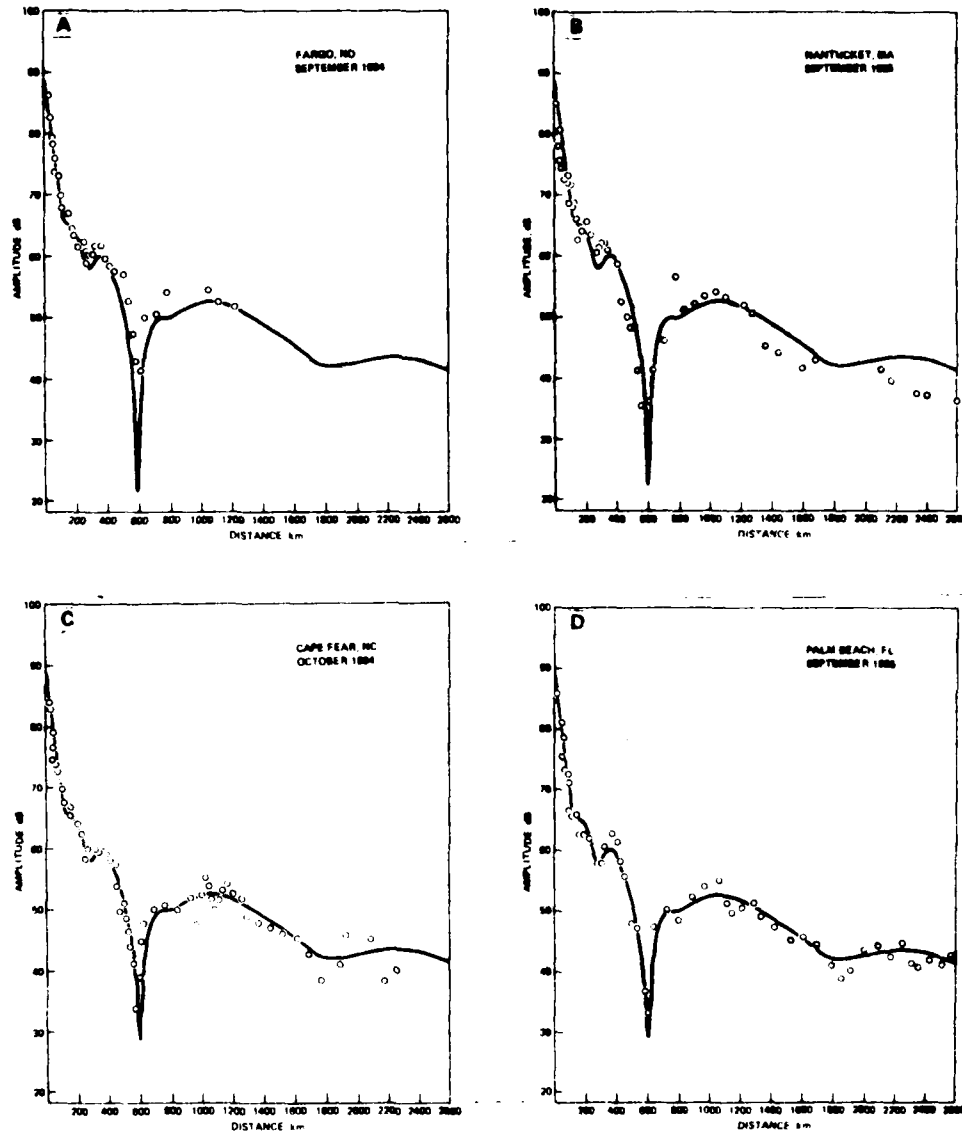
Propagation Path: Nine radials outward from Fort Collins, Colorado
                    (daytime)
Ground Conductivity: Land, σ = 0.01 mhos/meter
Transmitter: WWVL, Fort Collins, Colorado at 20 kHz
Date: September 1964, 1965; October 1964; January 1966; February 1966.
Electron Density Profile: β = 0.3 km^{-1}, h' = 72 km with the base of
                            the ionosphere at 30 km.
Method of Computation: Horizontally homogenous waveguide

A-22

Figure 19.   (CONTINUED) (Fall) (20 kHz)

A-23
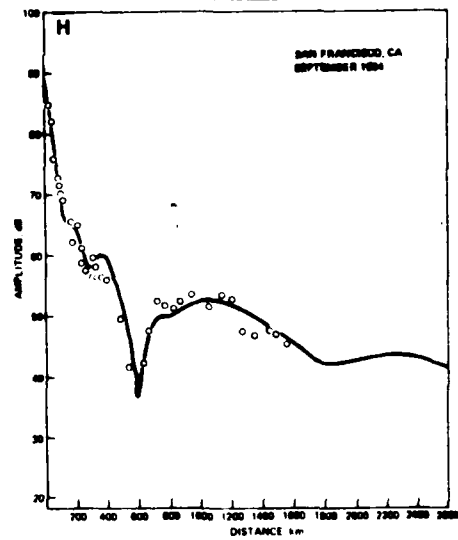
Figure 19. (CONTINUED) (Fall, Winter) (20 kHz)
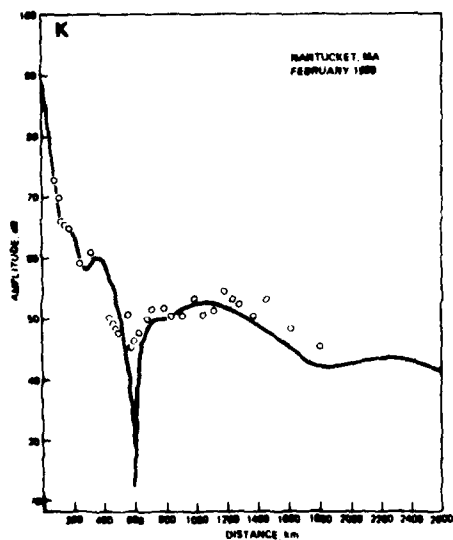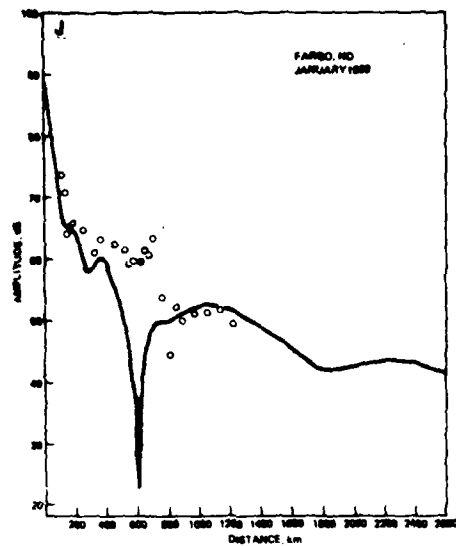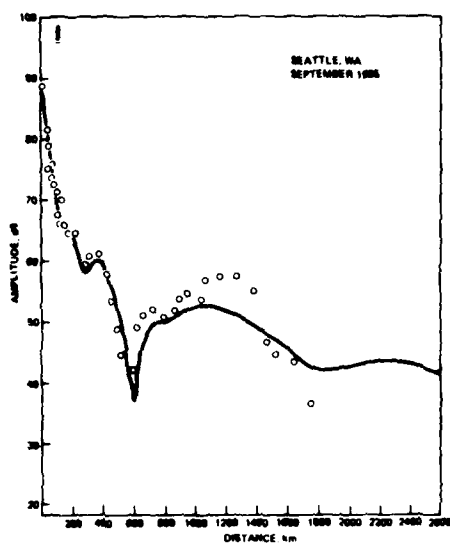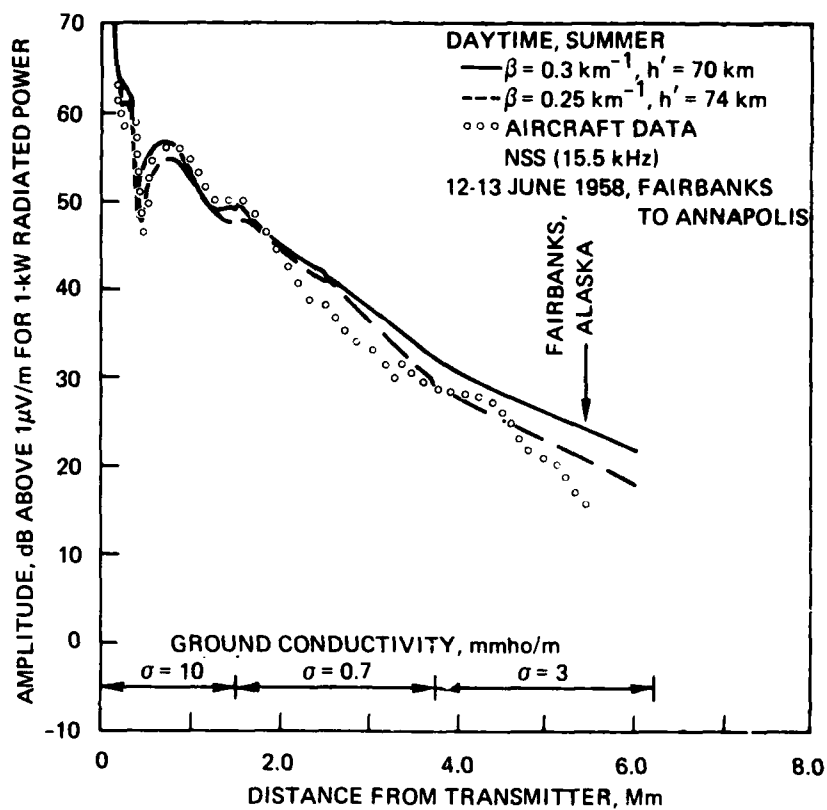

FREQ = 20 kHz
DATA = O
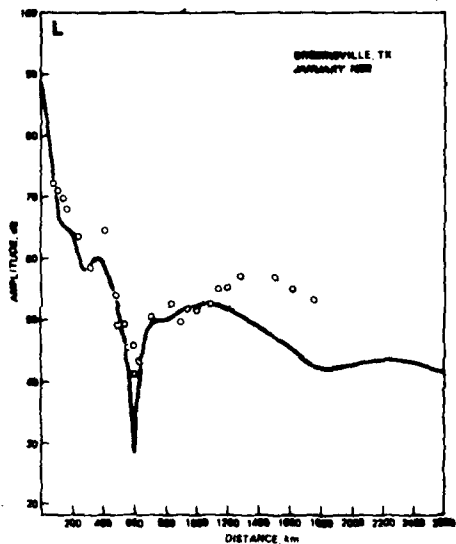
Figure 20. High-Latitude Propagation

Flight Path: Fairbanks, Alaska to Annapolis, Maryland, (daytime)
Ground Conductivity: Various land conductivities
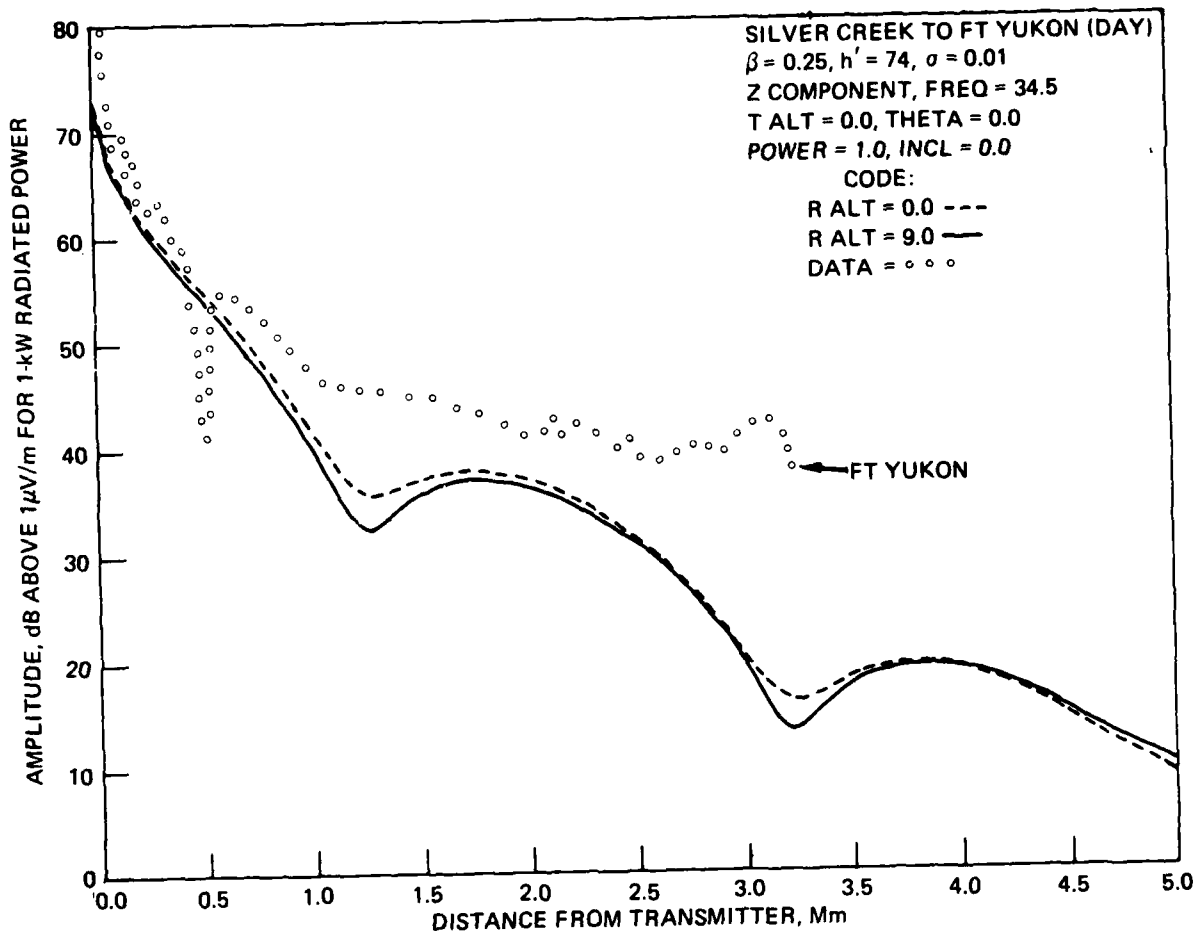Transmitter: NSS, Annapolis, Maryland, 15.5 kHz
Date: June 1958
Electron Density Profiles: $\beta = 0.3$ km^{-1}, h' = 70 km with the base of
                            the ionosphere at 30 km, and
                            $\beta = 0.25$ km^{-1}, h' = 74 km with the base of
                            the ionosphere at 40 km.
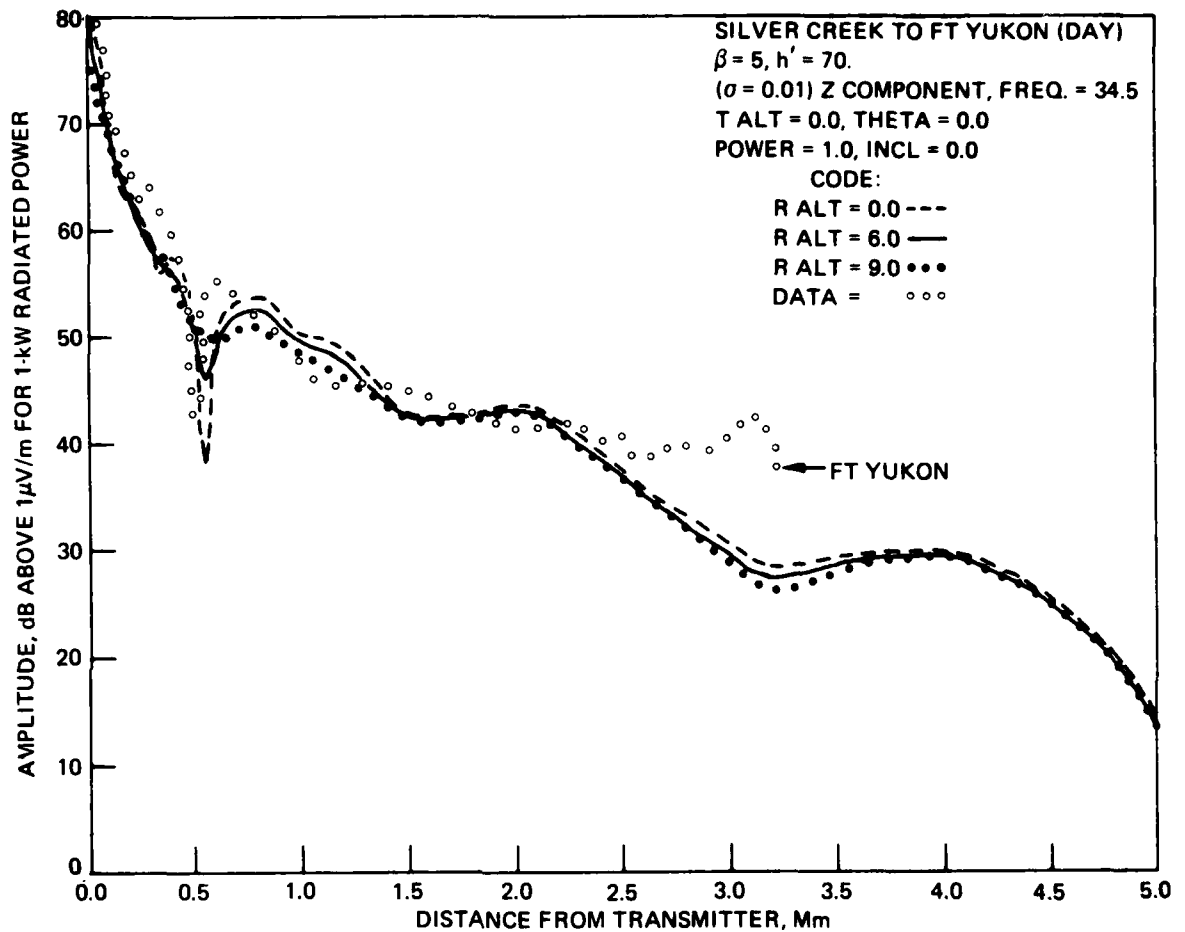Method of Computation: WKB approximation
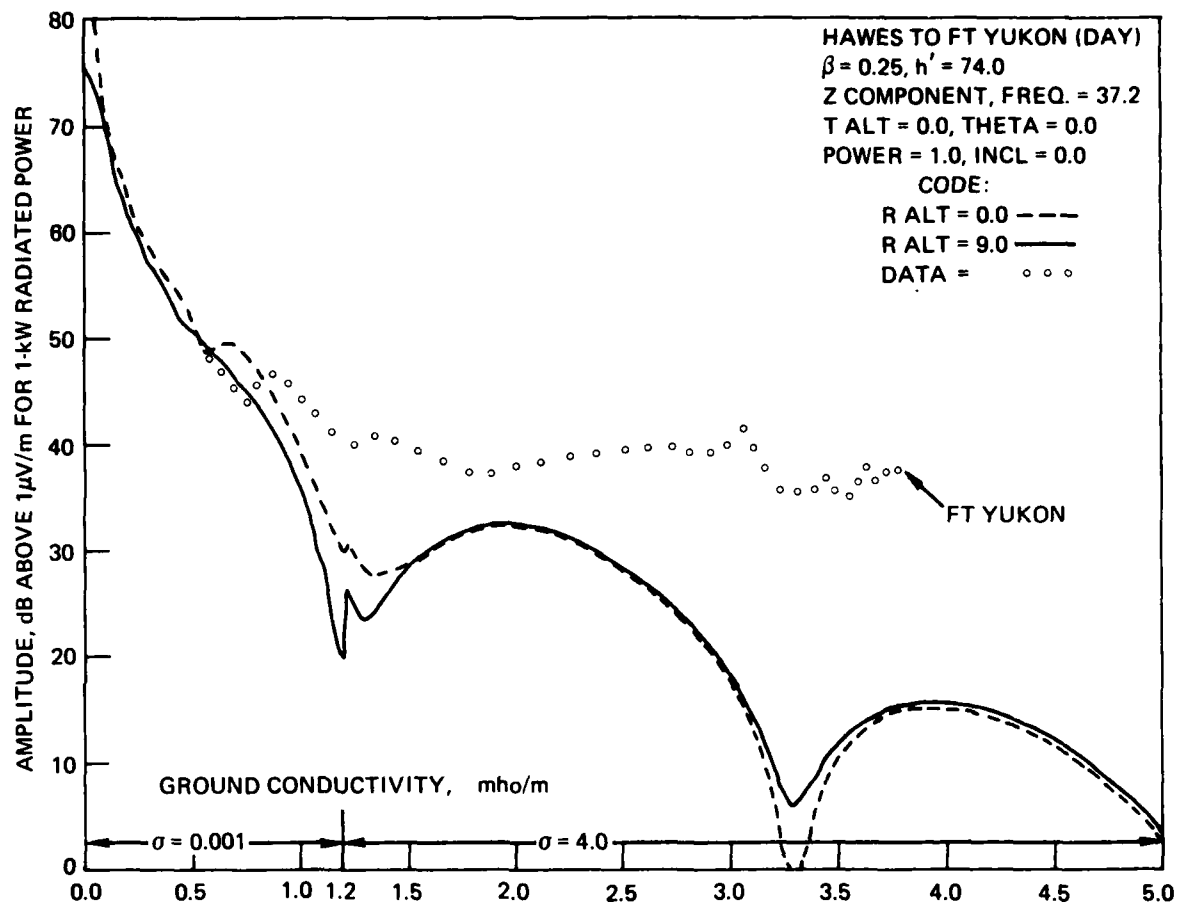
A-25

Figure 21. High-Latitude Propagation

Flight Path: Silver Creek to Fort Yukon, Alaska (daytime)
Ground Conductivity: Land, σ = 0.01 mhos/meter
Transmitter: Silver Creek, Nebraska, 34.5 kHz
Date: 26 January 1970
Electron Density Profile: β = 0.25 km^{-1}, h' = 74 km with the base of
the ionosphere at 20 km.
Method of Computation: Horizontally homogenous waveguide

A-26

Figure 22. High-Latitude Propagation

Here the propagation parameters are the same as in figure 21 except that the electron density profile used is ß = 0.5 km^{-1}, h' = 70 km with the base of the ionosphere at 50 km.

Figure 23. High-Latitude Propagation

Flight Path: Hawes, California to Fort Yukon, Alaska (daytime)
Ground Conductivity: Land, $\sigma = 0.001$ mhos/meter and sea water, 4
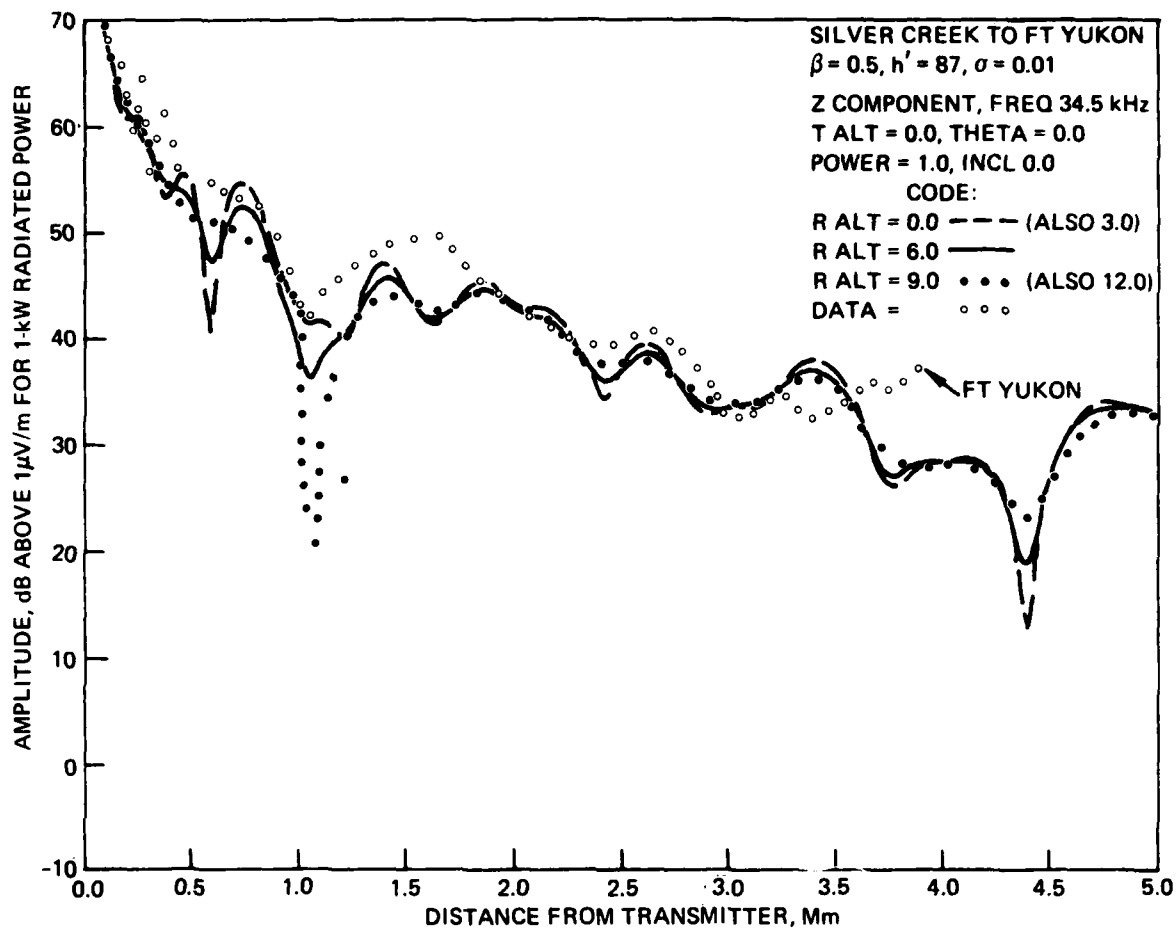   mhos/meter.
Transmitter: Hawes, California, 37.2 kHz
Date: 27 January 1970
Electron Density Profile: $\beta = 0.25$ km^{-1}, h' = 74 km with the base of
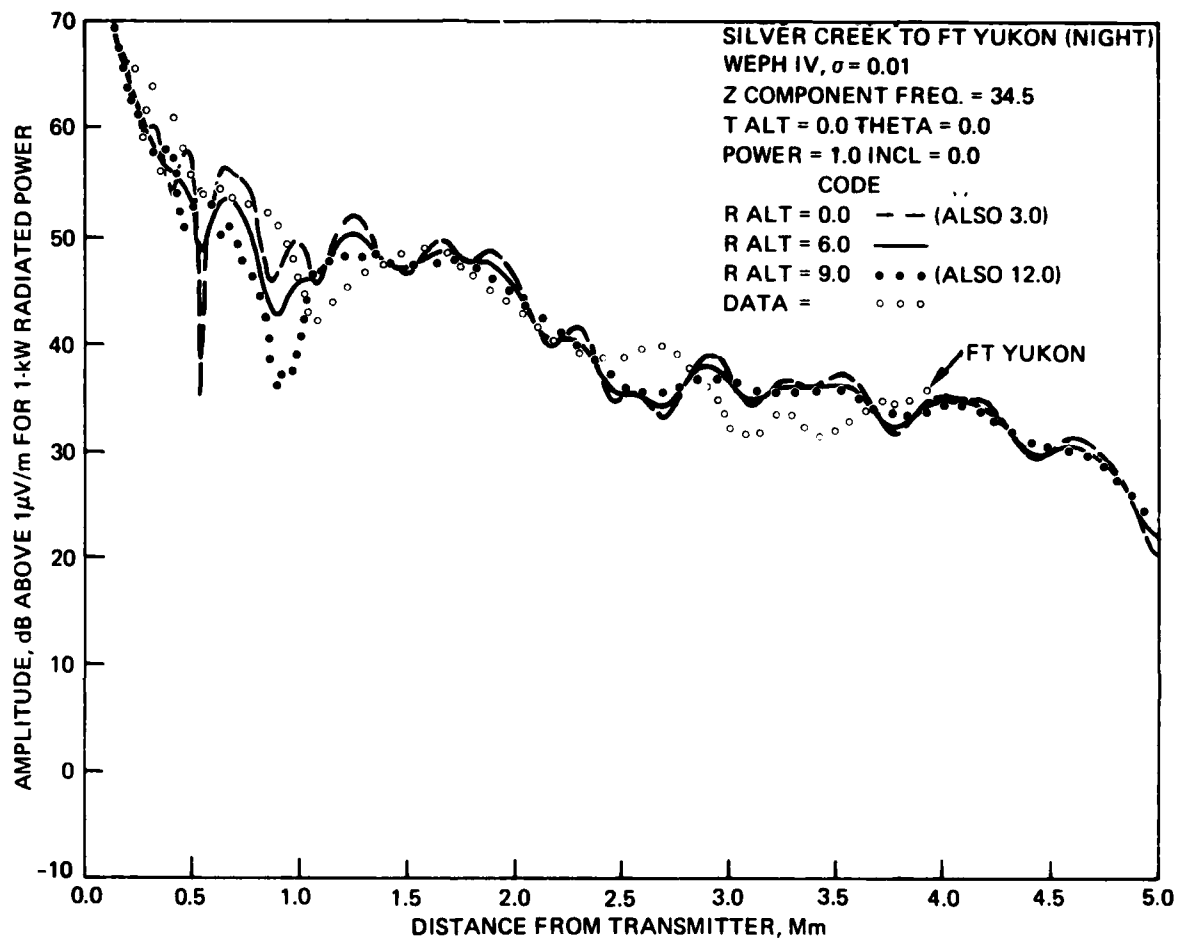   the ionosphere at 20 km.
Method of Computation: WKB approximation

A-28

Figure 24. High-Latitude Propagation
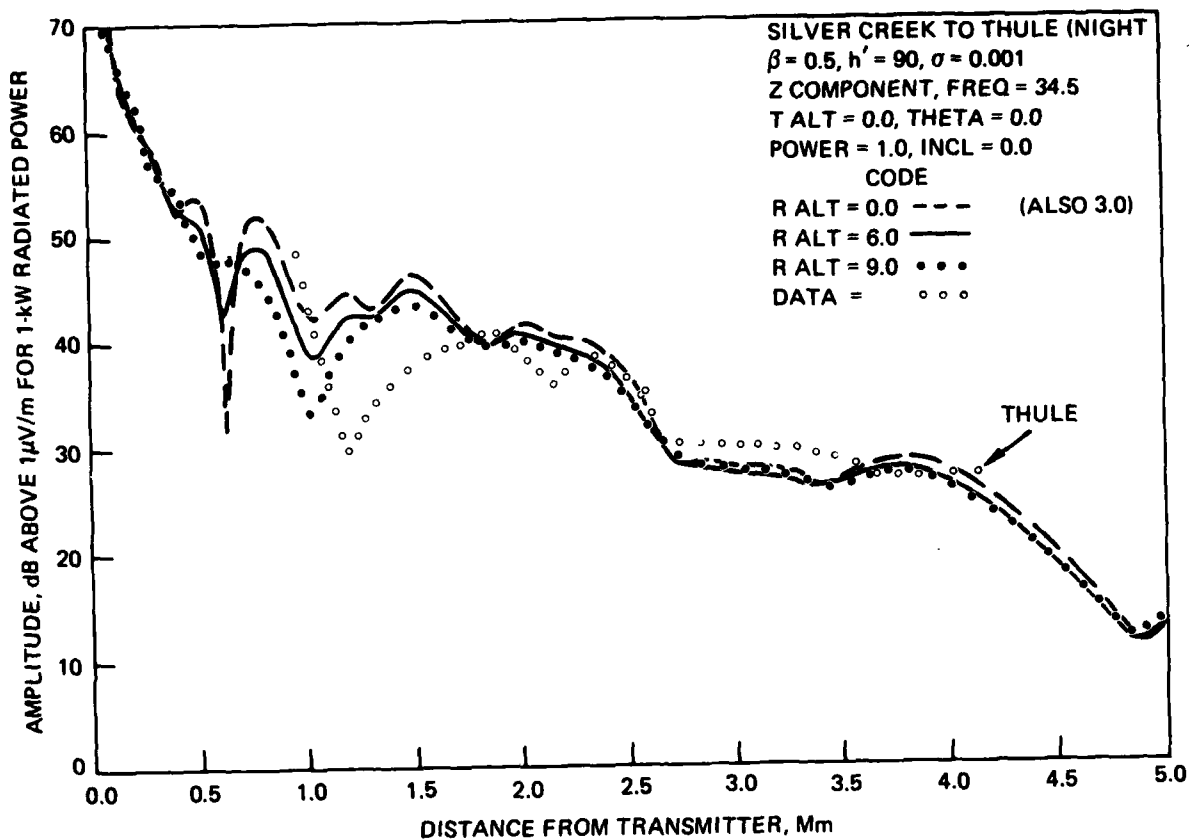

Flight Path: Silver Creek to Fort Yukon, Alaska (nighttime)
Ground Conductivity: Land, σ = 0.01 mhos/meter
Transmitter: Silver Creek, Nebraska, 34.5 kHz
Date: 30 January 1970
Electron Density Profile: $\beta = 0.5 \text{ km}^{-1}$, h' = 87 km with the base of
                              the ionosphere at 50 km.
Method of Computation: Horizontally homogenous waveguide

A-29

Figure 25. High-Latitude Propagation

SILVER CREEK TO FT YUKON (NIGHT)
WEPH IV, $\sigma = 0.01$
Z COMPONENT FREQ. = 34.5
T ALT = 0.0 THETA = 0.0
POWER = 1.0 INCL = 0.0
CODE
R ALT = 0.0 — — (ALSO 3.0)
R ALT = 6.0 ———
R ALT = 9.0 • • • (ALSO 12.0)
DATA = o o o

FT YUKON

Here the propagation parameters are the same as in
Figure 24 except that the electron density profile used
is WEPH IV.

Figure 26. High-Latitude Propagation


Flight Path: Silver Creek to Thule, Greenland (nighttime)
Ground Conductivity: Land only, σ = 0.001 mhos/meter
Transmitter: Silver Creek, Nebraska, 34.5 kHz
Date: (probably 1970)
Electron Density Profile: β = 0.5 km^{-1}, h' = 90 km with the base of
                                        the ionosphere at 50 km.
Method of Computation: Horizontally homogenous waveguide

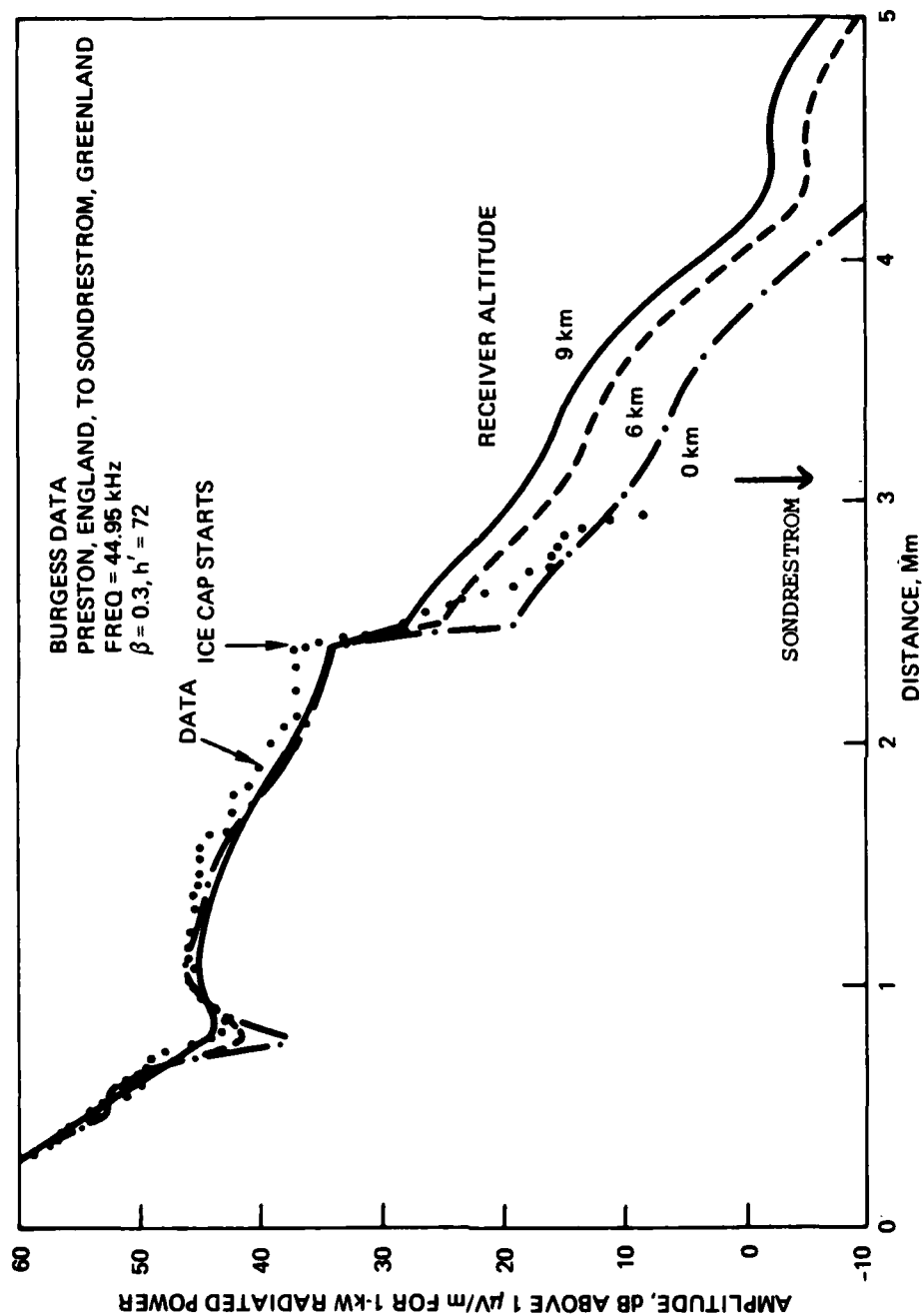Figure 27. High-Latitude Propagation
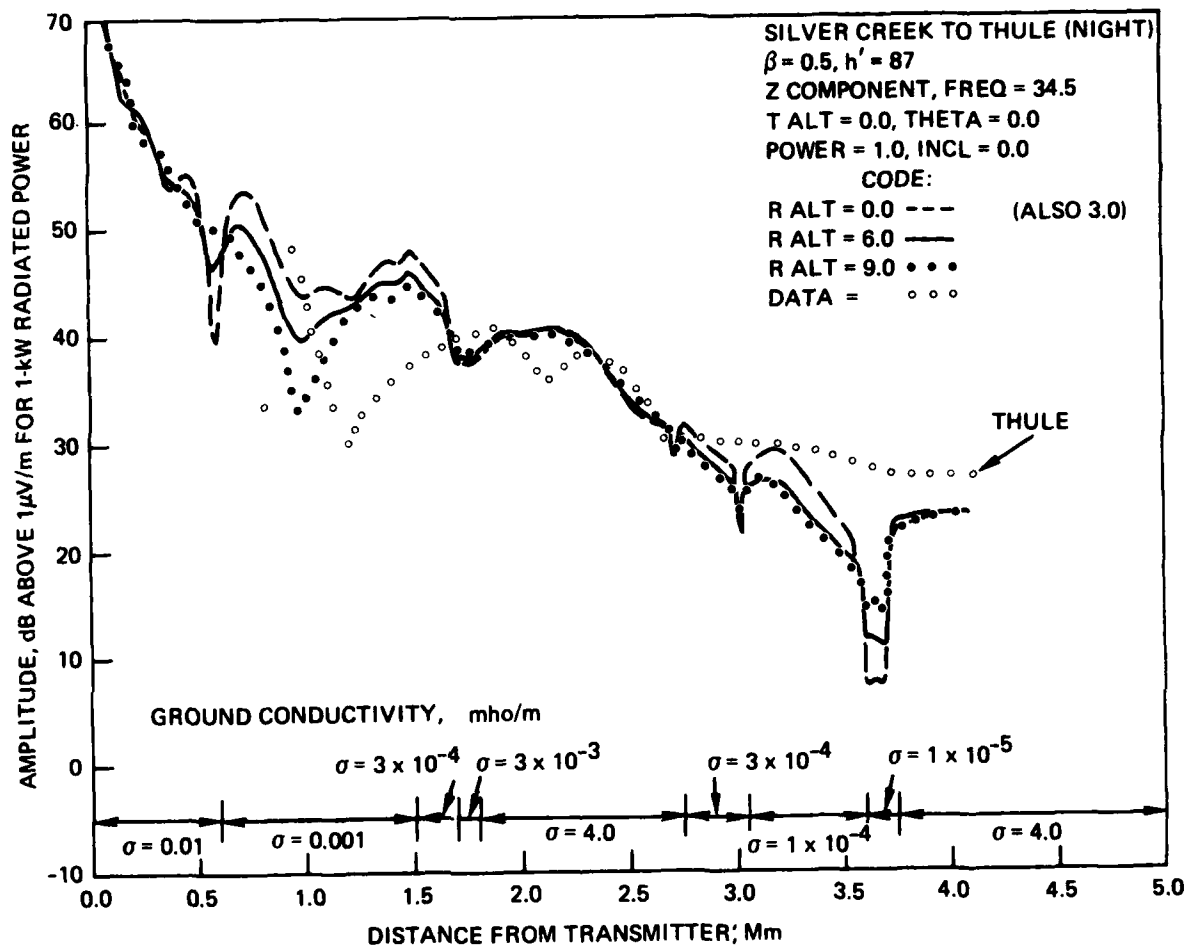
Flight Path: Silver Creek to Thule, Greenland (nighttime)
Ground Conductivity: Land, sea, and ice variations
Transmitter: Silver Creek, Nebraska, 34.5 kHz
Date: (probably 1970)
Electron Density Profile: $\beta = 0.5$ km^{-1}, h' = 87 km with the base of
                          the ionosphere at 50 km.
Method of Computation: WKB approximation

A-32

Figure 28. High-Latitude Propagation
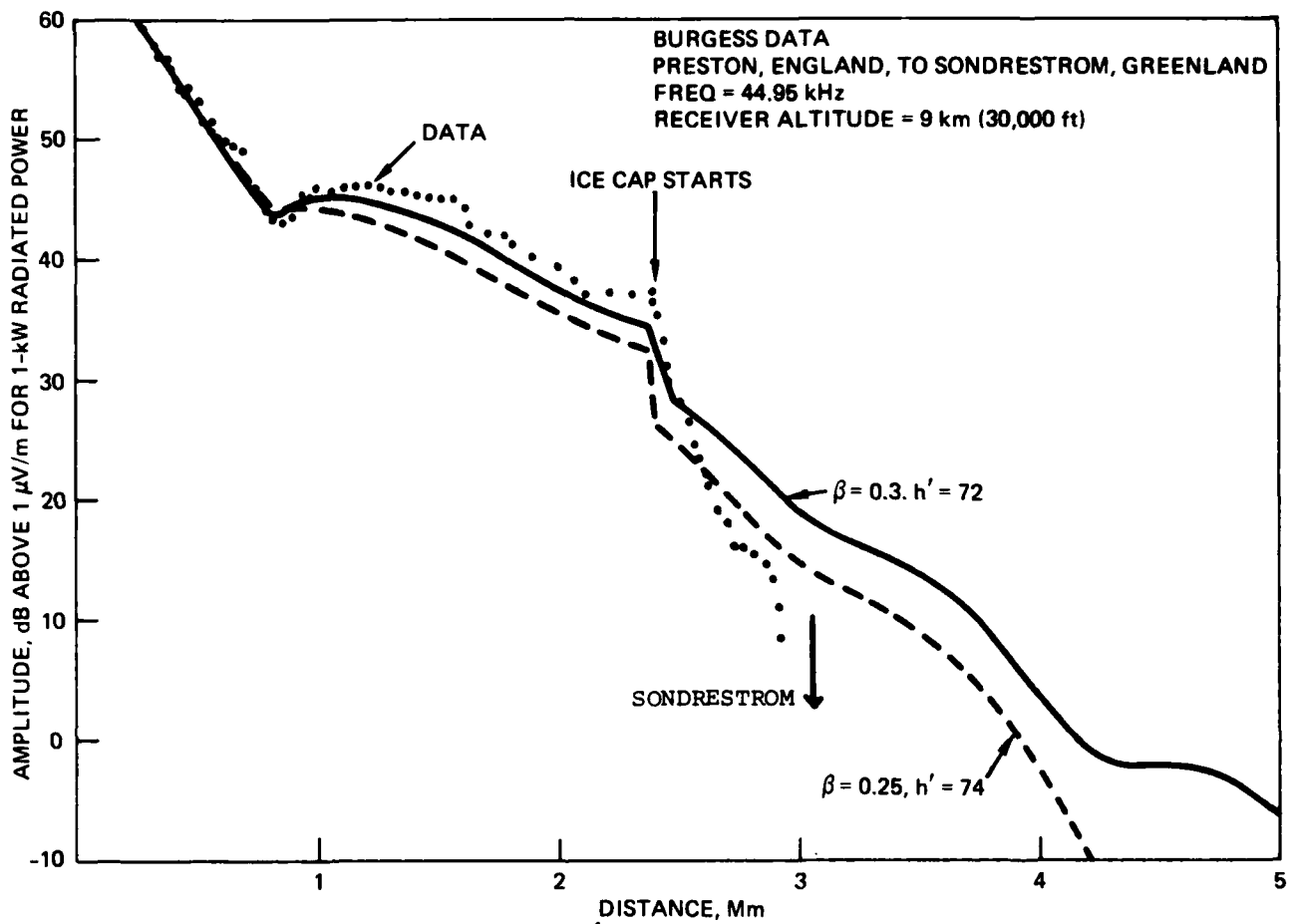
Flight Path: England to Sondrestrom, Greenland (daytime)
Ground Conductivity: Sea water, 4 mhos/meter; Greenland ice cap,
                     10^{-5} mhos/meter.
Transmitter: GYN, Preston, England (45 kHz)
Date: July 1970
Electron Density Profiles: $\beta = 0.3$ km^{-1}, h' = 72 km with the base of
                           the ionosphere at 30 km and,
                           $\beta = 0.25$ km^{-1}, h' = 74 km with the base of
                           the ionosphere at 40 km.
Method of Computation: WKB approximation
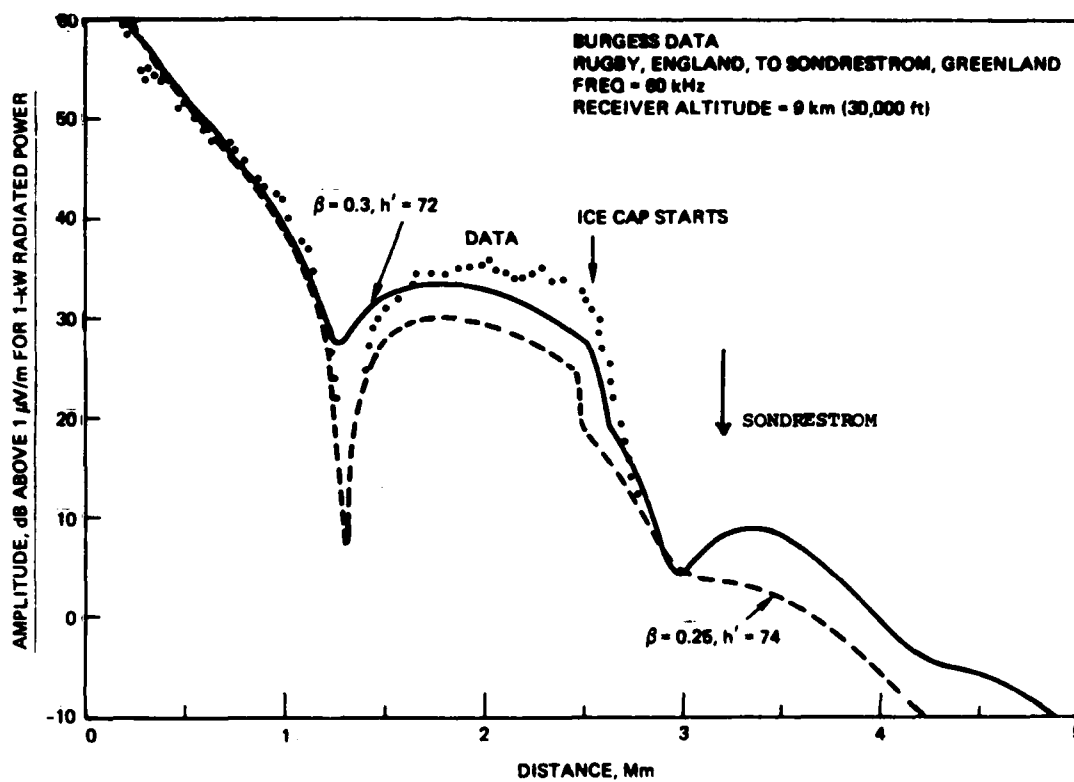
A-33

Figure 29. High-Latitude Propagation

Propagation parameters are the same as figure 28 except that only the $\beta = 0.3$ km^{-1}, h' = 72 km profile is shown. Field strengths are computed for receiver altitudes (RALT) of 0, 6, and 9 km.

Figure 30. High-Latitude Propagation

Flight Path: England to Sondrestrom, Greenland (daytime)
Ground Conductivity: Sea water, 4 mhos/meter; Greenland ice cap,
                        10^{-5} mhos/meter.
Transmitter: MSF, Rugby, England (60 kHz)
Date: July 1970
Electron Density Profiles: $\beta = 0.3$ km^{-1}, h' = 72 km with the base of
                            the ionosphere at 30 km and,
                            $\beta = 0.25$ km^{-1}, h' = 74 km with the base of
                            the ionosphere at 40 km.
Method of Computation: WKB approximation

A-35

Figure 31. High-Latitude Propagation
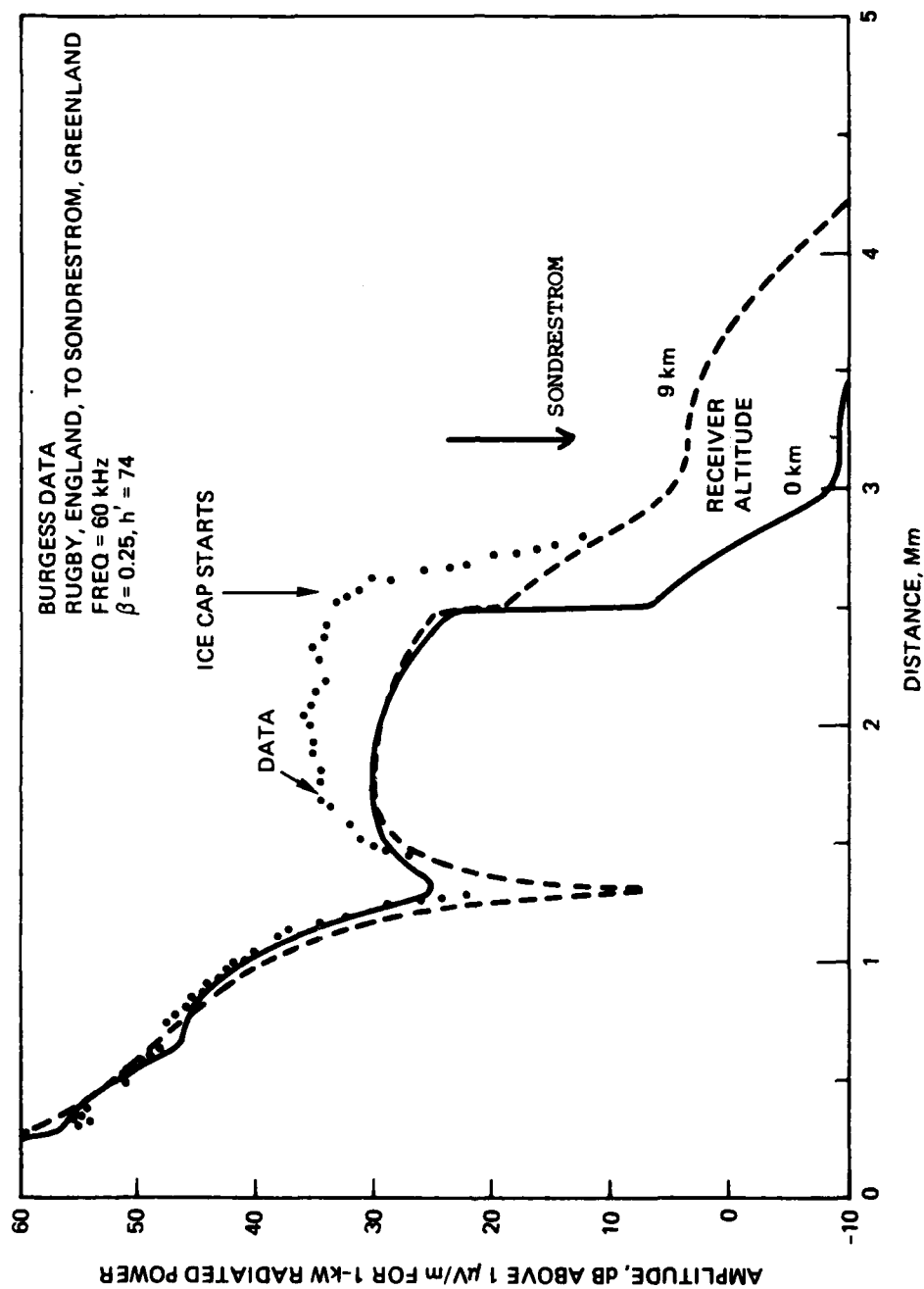
Propagation parameters are the same as figure 30 except that only the $\beta = 0.25$ km^{-1}, h' = 74 km profile is shown. Field strength values are computed for receiver altitudes (RALT) of 0 and 9 km.

A-36

Figure 32.   High-Latitude Propagation
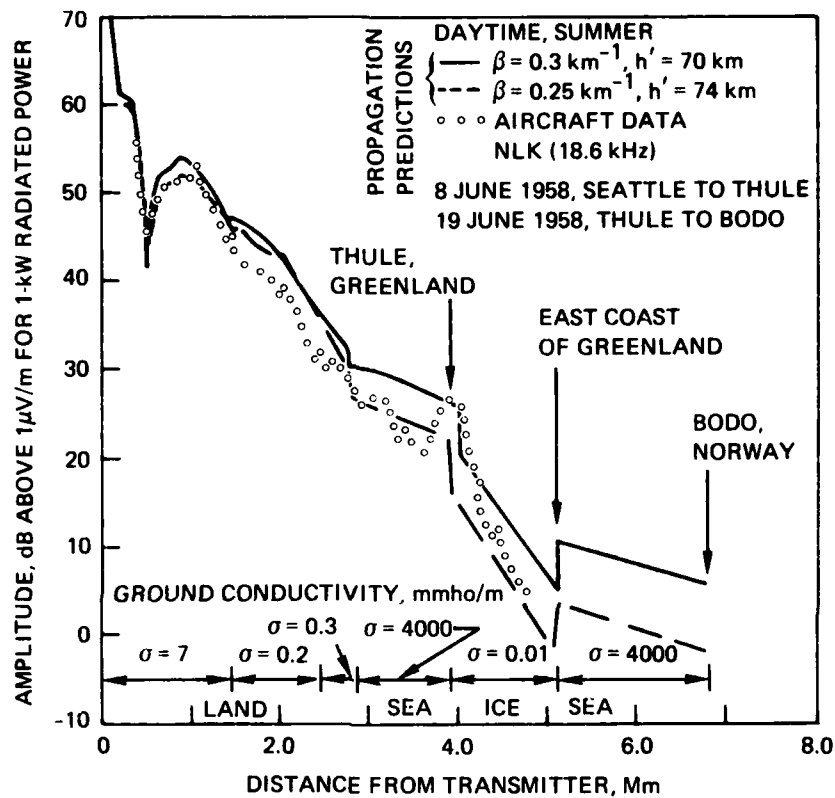
Flight Path: Seattle, Washington across Canada and over the Greenland
                ice cap.
Ground Conductivity: Various values of land, sea, and ice along the path.
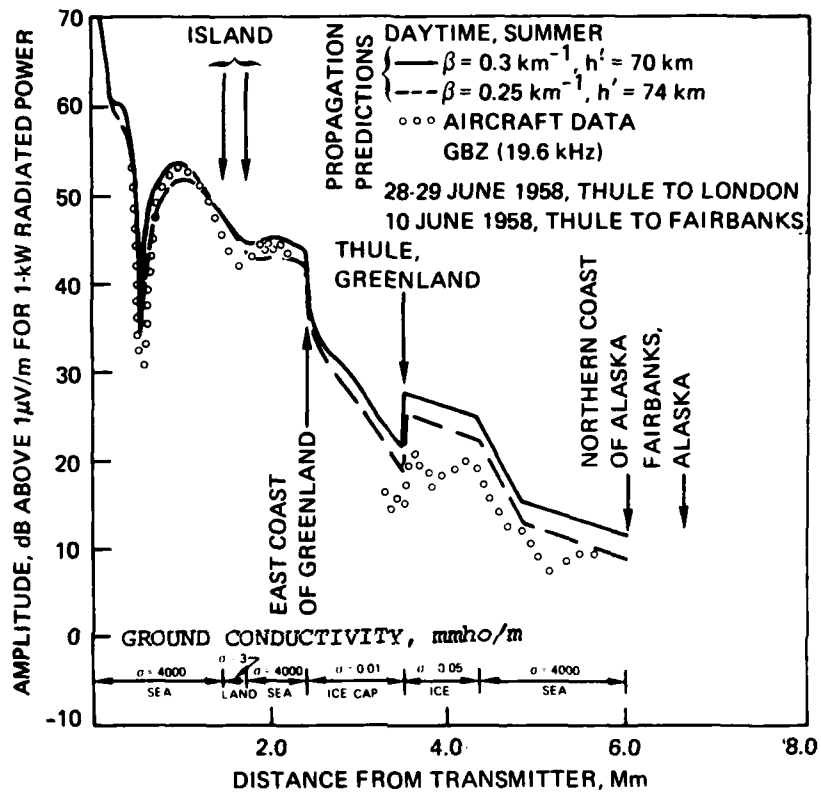Transmitter: NLK, Seattle, Washington (18.6 kHz)
Date: June 1958
Electron Density Profiles: $\beta = 0.3$ km^{-1}, h' = 70 km with the base of
                             the ionosphere at 30 km and,
                             $\beta = 0.25$ km^{-1}, h' = 74 km with the base of
                             the ionosphere at 40 km.
Method of Computation: WKB approximation.

A-37

Figure 33. High-Latitude Propagation

Flight Path: Thule, Greenland across the ice cap to London, England
                and Thule to Fairbanks, Alaska.

Ground Conductivity: Various values of land, sea, and ice along the
                       path.

Transmitter: GBZ, Rugby, England (19.6 kHz)

Date: June 1958

Electron Density Profiles: $\beta = 0.3$ km^{-1}, h' = 70 km with the base
                             of the ionosphere at 30 km and,
                             $\beta = 0.25$ km^{-1}, h' = 74 km with the base of
                             the ionosphere at 40 km.

Method of Computation: WKB approximation.

A-38
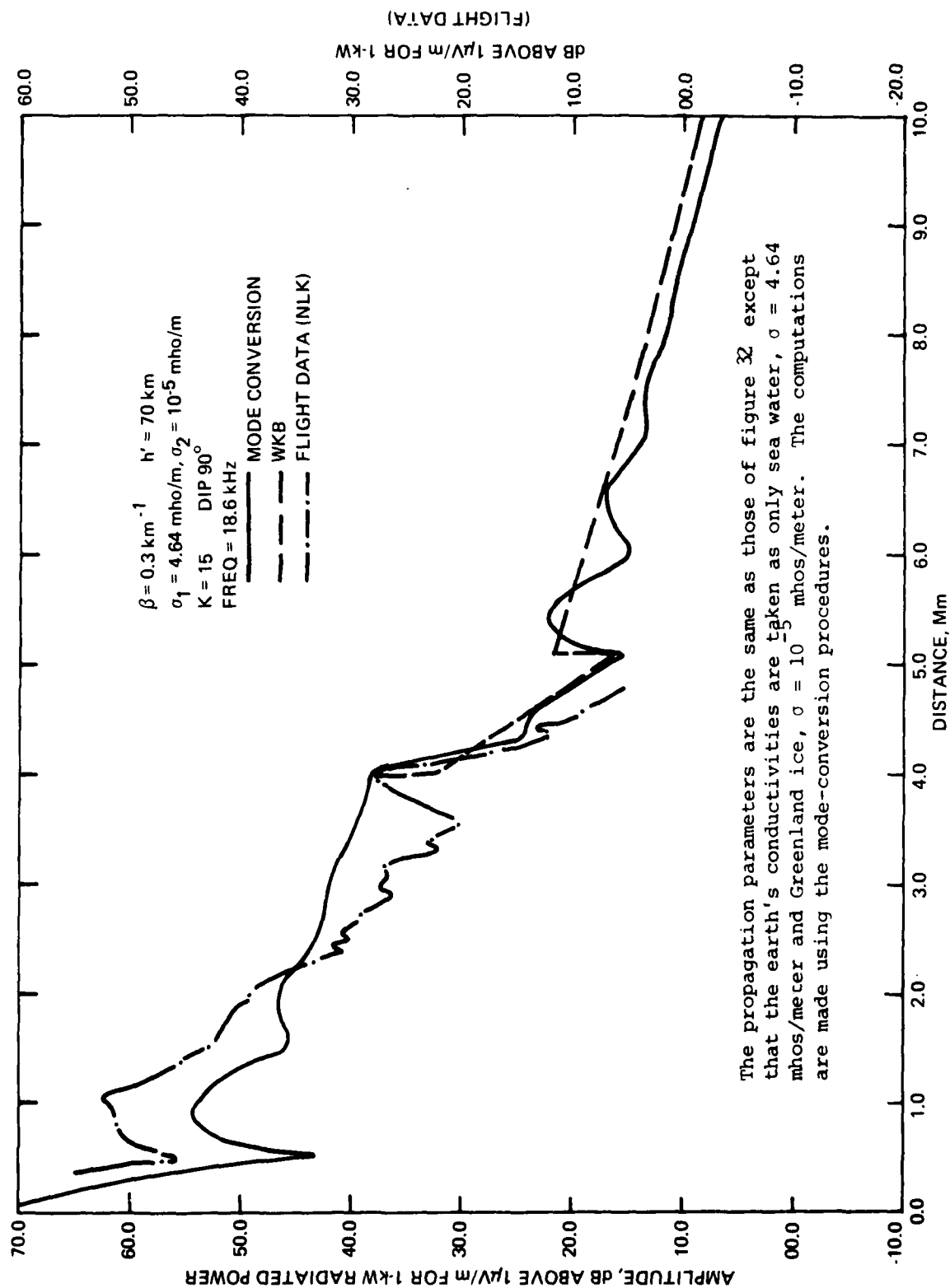
Figure 34. High-Latitude Propagation

Figure 35. High-Latitude Propagation

The propagation conditions are the same as those of figure 33 except that the earth's conductivities are taken as only sea water, $\sigma = 4.64$ mhos/meter and Greenland ice, $\sigma = 10^{-5}$ mhos/meter. The computations are made using the mode-conversion program.
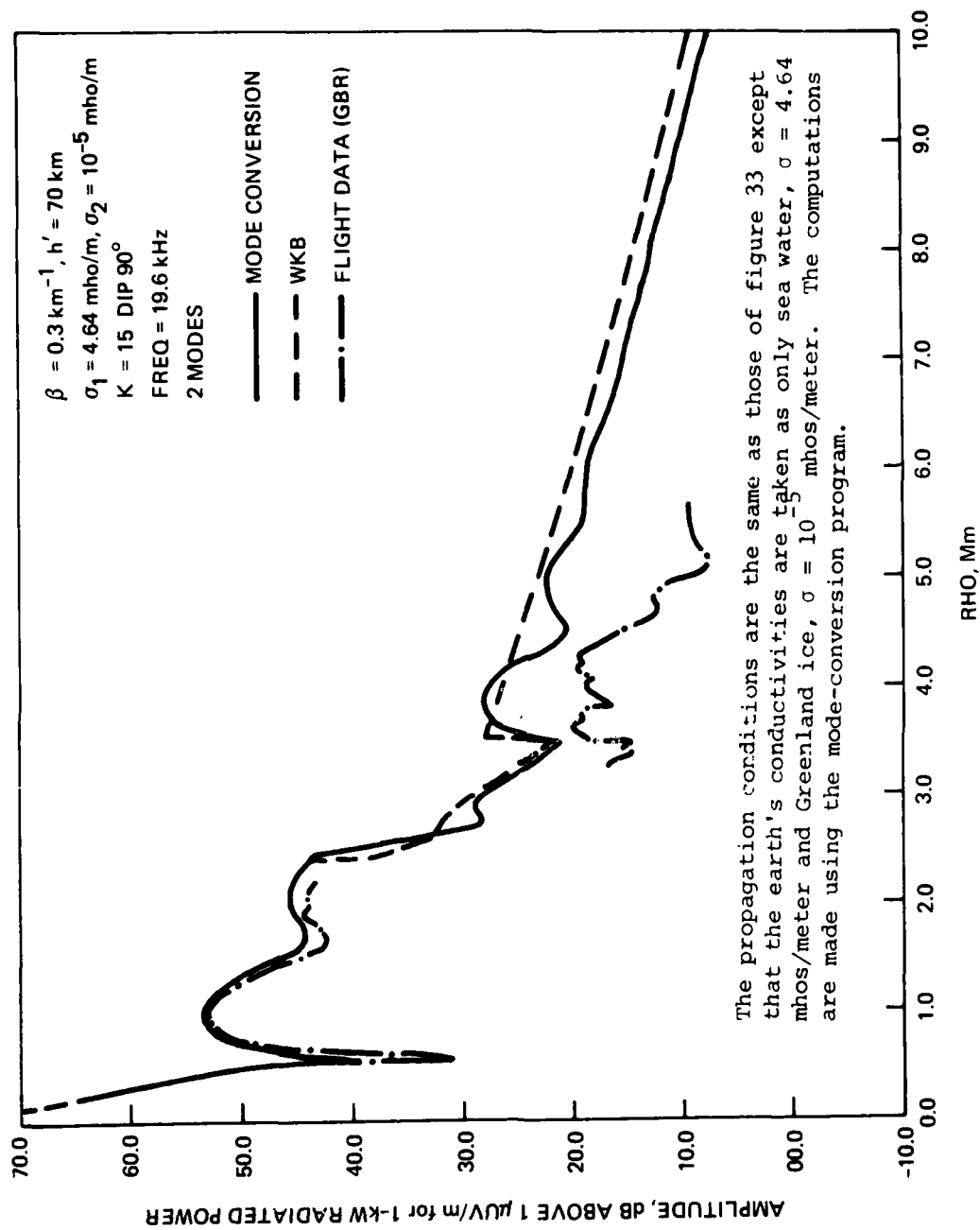
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